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An Investigation into the Use of Digital Sketching during the Early-Middle Design Phases in Industrial Design Practice

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ABSTRACT

In industrial design, an increasing number of new and emerging digital design tools are available for designers to employ for externalising, communicating and presenting design concepts. Digital Sketching, as one of these tools, shows powerful affordances in theory that could help industrial designers achieve effective design representations in a timely manner. However, the use and applications of this tool seem to be relatively conservative based on empirical observations in industry, suggesting Digital Sketching could be a somewhat untapped design resource. This thesis aims to investigate and understand the use of Digital Sketching during the Early-Middle phases of the industrial design process, which then contributes a deepening of the domain knowledge of Digital Sketching and explores opportunities for its more effective use in practice.

Three research questions are posed to provide a more comprehensive and up-to-date understanding of Digital Sketching. Research question 1, "How to compare Digital Sketching with other design visualisation tools in the industrial design field?", is posed to define a basis to examine the use of Digital Sketching in comparison with its most common neighbouring tools (i.e., Traditional Sketching and CAD). The Design Tool Characteristics (DTCs) framework is created for answering this question. The theoretical affordances of Digital Sketching and the bi-polarised affordances of its neighbouring tools are clarified, concurring with the original research motivation. Research question 2, "How does Digital Sketching manifest in industrial design practice during the Early-Middle design phases?", is posed to understand the motivations and concerns of designers when using the three tools. Building on the manifestation, research question 3, "Could Digital Sketching be a 'pathway' to ease transitions between Traditional Sketching and CAD in industrial design practice?", is posed to explore the merits of using Digital Sketching as a transitional tool.

Twelve semi-structured interviews and eight unobtrusive observation sessions with designers were conducted collecting data to answer these questions. With the proposed DTCs framework, the manifestation of Digital Sketching and its neighbouring tools is described in terms of the most frequently discussed characteristics. Findings show that designers have different preferences for tools and DTCs in different conditions of use (externalisation, internal communication and external communication) that occur during different phases of the design process. The patterns of use and applications of Digital Sketching in each tool-use condition are explained accordingly. Results concur with the original research motivation showing how Digital Sketching is primarily used for polished sketches in external communication with clients and other stakeholders. However, the study results indicate that Digital Sketching can also be a useful transi-

tional tool in assisting externalisation activities for designers themselves. Furthermore, some user-related limitations on adaptability are noted, some of which are related to the designers' learning process of Digital Sketching in previous formal education. For internal communication with project members, Digital Sketching is not yet considered an ideal tool or transitional tool to use. However, this pattern of use could change with the development of relevant technologies.

In conclusion, the thesis proposes the DTCs framework as a basis for analysing and understanding design visualisation tools in industrial design, which can be used in future studies of other leading-edge design tools. The thesis also contributes a more comprehensive and up-to-date understanding of Digital Sketching to deepen the domain knowledge and free up design resources in the community. It shows that Digital Sketching could provide more diverse patterns of use and applications in practice, facilitating industrial designers to achieve effective design outcomes in a timely manner. Finally, the thesis concludes that embracing Digital Sketching and relevant technologies in design education and industry is critical to shaping the skill sets and mindsets of current and future designers. With this in mind, further work and research projects are recommended for the future.

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DECLARATION

I, Wenwen Zhang, declare that the thesis submitted is my own original work. To the best of my knowledge, the thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing. I declare that the thesis does not breach copyright or other intellectual property rights of a third party. I declare that the thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution of higher learning.

Wenwen Zhang

Signature: 

Date: 16 December 2020

LIST OF PUBLICATIONS AND PRESENTATIONS

Publications:

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LIST OF TERMS AND ABBREVIATIONS

CCs Capability-related Characteristics of Design Tools ii, 46, 51, 53, 61, 65, 78, 93, 123, 177, 224, 241

DRM Design Research Methodology 10, 38, 77, 94, 247

DTCs Design Tool Characteristics ii, v, ix, x, xii, xiv, 8, 9, 11–14, 16, 37, 42, 45, 46, 53, 54, 58–61, 69, 71, 72, 75, 76, 78, 87, 91, 94, 96, 98, 100, 103, 110, 122, 124, 136, 138, 141, 145, 147, 149, 151, 153, 154, 171, 174–182, 184–188, 190–192, 194, 195, 199–202, 205–222, 224, 226–228, 230–232, 237, 242–244, 246

HCI Human-Computer Interaction 48

IDSA Industrial Designers Society of America 39, 93, 155, 156

UCs User-related Characteristics of Design Tools . ii, 51–53, 61, 65, 70, 78, 87, 88, 121, 123, 127, 177, 187, 191, 220–222, 224, 227, 228, 239, 241

UTCs Five Universal Tool Characteristics 8, 42, 44, 46, 47

UxD User Experience Design 48

VDI The Association of German Engineers 63

WDO World Design Organization 68

CAD Instead of referring to the computer-aided-design, CAD here refers to specific 3D computer modelling software products used in the design process, i.e. Solidworks, Rhinoceroes, Alias. x, 2–5, 7, 8, 27, 28, 57, 58, 67, 72, 78, 82–84, 100, 101, 192, 193, 198

Digital Sketching Digital Sketching is a subcategory of the defined Sketching that is supported by digital media, which can be applied with hand, mouse or other digital pen-like device. i, ii, vii, viii, x, 1, 2, 4–10, 13, 14, 16, 18, 24, 25, 27–38, 40, 41, 50, 53–59, 67, 68, 75, 76, 79, 80, 82–84, 87, 89, 100, 192–194, 198, 229

Industrial Design Industrial Design is a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experiences....., 80, 84

Manifestation The patterns of use and applications of design visualisation tools. 81, 84, 91, 93, 94, 99, 110, 126, 129, 131, 147, 149, 154, 171, 179, 182, 191, 199, 205, 241, 242, 244

Sketching Sketching here refers to a technique applied in design fields, which is used for quickly generating and visualising ideas with specific media, namely traditional media and digital media. Sketching here is separated from doodling, drawing, painting etc. that used in arts.....i, 18–25, 27–31, 48, 72

Traditional Sketching Traditional Sketching here refers to freehand sketching with traditional media which usually means pen and paper. . x, 2–8, 23, 24, 28, 29, 31–35, 40, 41, 50, 55–58, 67, 78, 82–84, 100, 101, 192, 193, 198

INTRODUCTION

Rapidly emerging digital visualisation tools offer significant benefits to industrial designers in regard to time efficiency and presenting photo-realistic design representations. Such tools include digital sketching, 3D CAD modelling, 3D printing, virtual reality devices, etc. Lutters et al. (2014) report that the selection of tools during design activity mostly rely on the designers' expertise and creativity. However, research shows that visualisation tools can inhibit designers' creativity and/or be time inefficient if used in the wrong context (Robertson and Radcliffe, 2009). Thus, a concern for designers is deciding which tools to use, and when, during the design process, to optimise time efficiency and achieve effective design outcomes.

Unfortunately, the choices of what tools to use and when to use them cannot be made only from knowing which tools are available. The more we understand the design tools and their alternatives, the greater chance we have to figure out their most suitable context and the better use of them in design practice. With the overall goal to improve the utilisation of design resources, and to achieve more effective design outcomes with more efficient use of design visualisation tools, this thesis aims to understand and explore the use of Digital Sketching (deliberate capitals throughout), which currently has limited use during the Early-Middle (deliberate capitals throughout) design phases in industrial design practice when considering its theoretical potential. Thus, the results might help deepen the understanding of the use of Digital Sketching in practice, improve the awareness of its application, and further inspire new ways of its utilisation.

Digital Sketching in Industrial Design

Scope of the Research

As illustrated in Figure 1, the discipline known as industrial design is determined as the scope of this research project on Digital Sketching. However, the literature review is conducted with a broader scope. This is partially due to the similarity of design

representations and tool-sets in certain 3D design fields, and the use of the same or similar tools in these fields could also reflect their use in industrial design to a high degree.

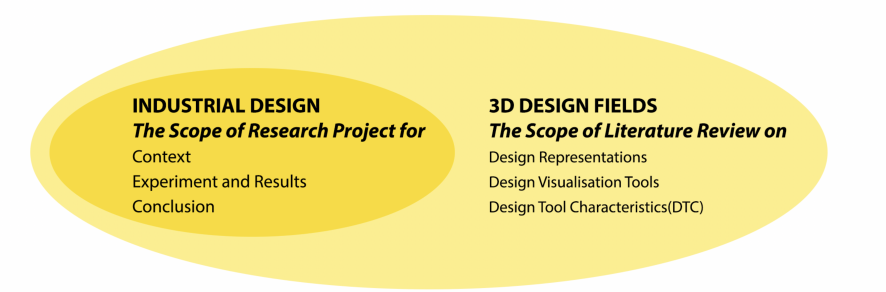


Fig. 1 The Scope of the Literature Review and Research Project

As the tool characteristic could be helpful for conducting analysis on design visualisation tools, a review of universal design tool characteristics is conducted within relevant 3D design fields. Similarly, a review-based investigation on the theoretical potential of Digital Sketching is conducted with the same scope to ensure the understanding of this tool is comprehensive. The limited number of studies on Digital Sketching in the industrial design field alone might be unable to offer a comprehensive view on the potential of this tool.

In addition, the design processes in these relevant 3D design fields are similar, which can reflect when and why to use the design tools. Even though "the design process is endless", according to Lawson (2006:123), design projects within three-dimensional design fields usually start from the conceptual design phase with using 2D ideation tools, and end up with design solutions created with 3D tools. Then, the solutions will be passed into manufacture/production/construction after prototyping and testing. The full product life cycle and beyond in the design process are not included in the discussion as the use of design visualisation tools are not usually applicable in these phases. This transition from 2D to 3D in these fields is also associated with another important affordance of Digital Sketching that needs to be examined in industrial design, namely 2D to 3D transition. It could only be reflected in these relevant 3D design fields rather than the 2D design fields, such as graphic design and illustration design. The troublesome transitions between the comparable and neighbouring tools of Digital Sketching in relevant 3D design fields, namely Traditional Sketching and CAD, are also noted in the literature.

The Troublesome Transitions in 3D Design Fields

As mentioned, to understand and explain the current context of design visualisation tools, a review of design representations and tools in the fields of three-dimensional (3D) design fields is conducted. There are noticeable transitions of design media and representation dimensions during the design process in these 3D design fields; e.g., industrial design, engineering design, architectural design, etc. Bouchard et al. (2006) report that designers usually start the design process with traditional sketches to explore potential solutions for the design problem, then later use CAD modelling to build 3D models to "visualise, compare, implement and validate" these solutions.

The nature of Traditional Sketching and its use in design process has been explored by many studies, which indicate that it is still the primary tool for designers to externalise, develop, test and communicate the design concepts in the early design phases (Goldschmidt, 2008; Buxton, 2010; Bouchard et al., 2006; Suwa et al., 2000; Goel, 1995; Tang, 2002; Yang and Cham, 2007; Tovey et al., 2003; Rohde, 2011; Römer et al., 2001). According to the literature, the tool characteristics of Traditional Sketching make it an intuitive, quick and well-utilised tool to fulfil the expectations of the earlier design phases (Self, 2011; Stones and Cassidy, 2010; Pei et al., 2011; Haggman et al., 2015).

In later design phases, CAD modelling is a sophisticated and powerful tool for refining, formalising, testing, presenting and delivering the design solutions to meet the requirements of industrial production, which was also invented to save effort and time for design and engineering use (Brown, 2009). However, the negative impact on designers' creativity from jumping into CAD too early has been already well-evidenced by research and agreed by designer practitioners (Brown, 2009; Robertson and Radcliffe, 2009; Römer et al., 2001). Studies report that there is a tendency towards increased use of CAD in the earlier design phases among design students and novice designers to pre-fulfil the requirements of the final deliverable or manufacturing/production. They may feel an urge to learn more about CAD and use it more often without considering the nature of the tool and knowing when to use the tool for effective design outcomes. Similarly, as Brown (2009) states in his study, "students feel the need to be proficient in CAD to keep up with industry-level design expectations that emphasise production." In general, researches show that a more appropriate time to use CAD in the design process is when the concept has attained a certain level of refinement in the later phases during the design process (Bouchard et al., 2006; Yang, 2005).

While Traditional Sketching and CAD both have excellent performance when being used in an appropriate manner, their characteristics are somewhat bipolarised compared

to each other. The bipolarisation of these two tools could be a double-edged sword. On the one hand, it enables them to assist the designers in achieving different design goals in different design phases. For example, the high support of the Lateral Transformation characteristic in Traditional Sketching could facilitate designers in exploring more design concepts, while the low support of this characteristic in CAD ensures that designers can use it to finalise their design concepts. On the other hand, the bipolarised nature of Traditional Sketching (deliberate capitals throughout) and CAD may also cause troublesome transitions when switching between them during the design process.

According to the literature and the author's observations at the workplace, transitions from 2D traditional sketches to 3D CAD models are considered as a huge consumption of designer's time and energy (McGown et al., 1998; Booth et al., 2016; Bilda and Demirkan, 2003; Self, 2011; Ranscombe and Bissett-Johnson, 2017). These transitions include, but are not limited to, the switching between using physical media and digital media (Bilda and Demirkan, 2003; Shih et al., 2015; Ibrahim and Rahimian, 2010) and the development from 2D concept sketches to 3D modelled solutions (Booth et al., 2016; Self, 2011; Aldoy and Evans, 2011; Tovey et al., 2003).

Besides, extending the use of Traditional Sketching is no longer practical to meet manufacturing requirements in the mass production era, and the earlier use of CAD has been proven to be anti-creative. Therefore, designers in 3D design fields have to face the transitions between these bipolar tools at some point during the design process. When navigating transitions, compromises must be made based on the designer's skills, preference of tools and so forth. Many of the compromises might not be ideal nor appropriate for conducting an efficient design process and achieving effective design outcomes. This raises the question of what tools and strategies can ease the transitions between the Traditional Sketching and CAD for better design outcomes and resource utilisation.

In this study, one particular field of 3D design fields, industrial design, is selected as the research scope to explore the solution of turning the troublesome transitions into a gradual shift of beneficial characteristics between Traditional Sketching and CAD.

The Potential Easing of Transitions by Using Digital Sketching

Through a preliminary investigation of design tools, some hybrid characteristics of Digital Sketching shed light on the solution of this conundrum in the industrial design field. Digital Sketching is a sketching tool built upon the digital platform that enables freehand or pen-like input. During the earlier phases of the design process, Traditional

Sketching is deemed as a quick, intuitive, and effort-saving way of capturing, developing and communicating concepts (Bouchard et al., 2006; Eiliat and Pusca, 2013). Similarly, as Bouchard et al. (2006) suggest in a study of Traditional Sketching, Digital Sketching might be able to keep these characteristics to allow designers to focus on the design concepts.

Arguably, using Digital Sketching during the design process as a stepping stone could ease the transitions between Traditional Sketching and CAD without severely impacting the designer's ideas. Besides, the digital operating platform of Digital Sketching has the potential for a more seamless transition with other digital modelling design tools; i.e., CAD Modelling. Hence, as illustrated in Figure 2, this study is designed to further understand the nature of Digital Sketching and explore the possibility of using it to ease the troublesome transitions between Traditional Sketching and CAD.

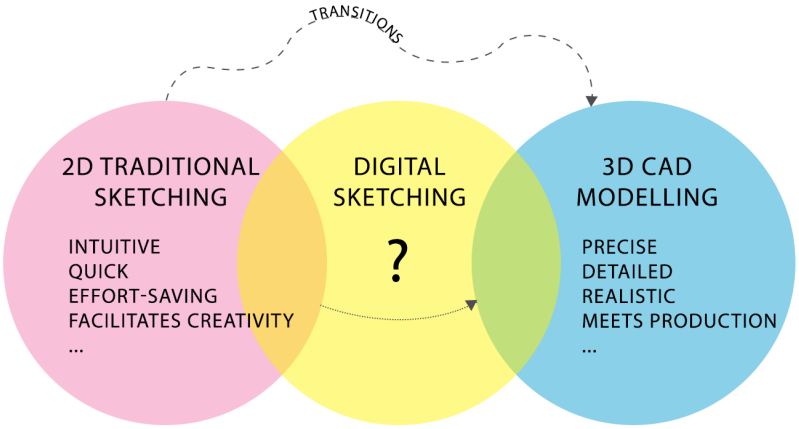


Fig. 2 The Potential Easing of the Transitions by Using Digital Sketching (Author's Own)

In terms of the transition from 2D to 3D, studies indicate that Digital Sketching has more potential than Traditional Sketching to help designers visualise their ideas by getting the right drawing perspectives (Ranscombe and Bissett-Johnson, 2017; Evans and Aldoy, 2016). Because of its hybrid characteristics, digital operating platform, and built-in features offered by the software, the transition from 2D sketches to 3D models could arguably be easier when using Digital Sketching (Ranscombe and Bissett-Johnson, 2017).

For example, Figure 3 shows the use of Digital Sketching for exploring design alternatives in a toy design project. Features of Digital Sketching, e.g. copy-paste, symmetry, and layers enabled the designers to quickly duplicate the initial head and body of the toy then easily explore the colour schemes and accessories (i.e. helmet), which can

contribute to building a more precise and detailed 3D mental image or mental model for the later design phases. In other words, hybrid characteristics of Digital Sketching seem to be helpful as a stepping stone for preparing designers in the 2D to 3D transition. Similarly, according to Evans and Aldoy (2016), the easier transition between Digital Sketching and 3D CAD Modelling is essential for considering the total digital design process, which has been discovered and discussed by researchers and design practitioners.

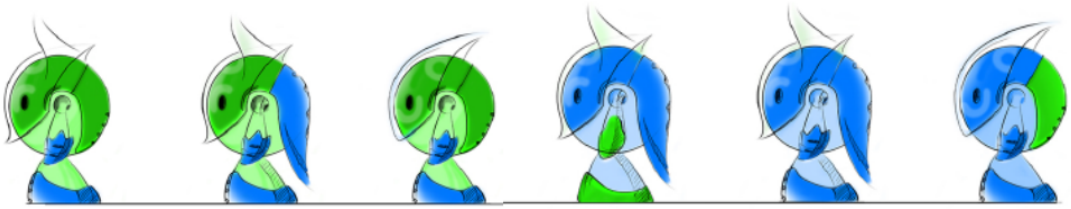


Fig. 3 Exploring Ideas With Digital Sketching (Author's Own)

Digital Sketching shows potential in easing the transitions regarding tool characteristics and operating platforms between the more bipolarised Traditional Sketching and CAD in industrial design. Hence, an in-depth investigation and discussion of the possibility of Digital Sketching to ease the transitions are expected.

Limited Use of Digital Sketching in Industrial Design Practice

In industrial design practice, the use of Digital Sketching is considerably limited and conservative compared to Traditional Sketching and CAD. According to the literature and a preliminary observation at various design institutions and workplaces, many designers and students only use Digital Sketching to digitalise and beautify their traditional sketches without further considering the potential of this tool (Johnson et al., 2009). In general, Digital Sketching is viewed simply as a mimic of pen-paper sketching (Eissen and Steur, 2007, 2012; Eissen and Roselien, 2019; Olofsson and Sjolen, 2005).

For example, a survey result of Bouchard et al. (2006) shows that 70 percent of 40 participating designers only use Traditional Sketching and 3D CAD modelling tools. So, considering the hybrid characteristics and features offered by Digital Sketching, its current use is relatively limited compared with that of Traditional Sketching and CAD, especially in the industrial design field. To summarise, it appears that the potential use of Digital Sketching in industrial design practice has yet to be fully realised.

Moreover, the number of studies on the role and use of Digital Sketching in industrial design practice is notably less than those on Traditional Sketching and CAD, even though the use of Digital Sketching has been conducted in practice ever since the creation of the first digital tablet (Evans, 2010). Since Digital Sketching has demonstrated certain characteristics and features that could potentially ease the troublesome transitions between the more commonly used Traditional Sketching and CAD, a lack of understanding of this tool could lead us to untapped design resources.

Therefore, a study of Digital Sketching would help us to understand the current use of Digital Sketching as well as to explore more ways to exploit it for a more efficient design process and more effective design outcomes, which is the overall aim of this project.

Understanding the Use of Digital Sketching in Practice

As mentioned above, to understand and explore the use of Digital Sketching in industrial design practice is the overall aim of this study. In relevant studies of design tools, an analysis of the design tool characteristics is suggested as a potential approach to rationalising the affordances of the design tool. However, the existing frameworks of design tool characteristics might be inefficient due to the depth of this study. It leads to a question of how to analyse and compare the use of Digital Sketching in practice. In addition to tools characteristics, it is also important to contextualise the use of design tools within the design process. The industrial design process is reviewed to set the foundation to understand what motivates designers to select and use a design tool, and when. With a clear research approach and context, a more up-to-date and comprehensive understanding of Digital Sketching in industrial design can be expected.

Characteristics of Design Visualisation Tools

Designers use design tools to externalise design ideas from their mind's eye to the real world (Self, 2011). Designers, nowadays, use an expanding inventory of design tools in design practice (Pipes, 2007; Self, 2011) due to emerging technologies. Despite the significant benefits of these emerging design visualisation tools, the selection of tools during the design process becomes more challenging for designers, especially for novice designers. Therefore, the study of various design tools is vital for ensuring the utilisation of available design resources. However, an effective approach for in-depth understanding and analysing Digital Sketching, as well as other design visualisation

tools in industrial design process, seems to be inadequately addressed in relevant studies. Hence, there is a need to survey the literature on the study of design tools to establish an effective approach, which has initialised the first research question of the study as follows.

Research Question 1: ***How to compare Digital Sketching with other design visualisation tools in the industrial design field?***

As Lutters et al. (2014) state, analysing characteristics of the techniques and tools is more efficient, credible and useful in capturing their essence rather than collecting endless lists of existing tools. Design tool characteristics can be used to describe a design tool by breaking down its entire property to universal, analysable and comparable factors (Self, 2011; Stolterman et al., 2009; Purcell and Gero, 1998). The key to effectively studying and understanding various design tools is to identify their comparable characteristics.

However, existing research on design visualisation tool studies and their resulting frameworks are either very specific to a certain tool or generalised at a level of designer behaviour (Self, 2011; Pei et al., 2011). Therefore, a more comprehensive framework of Design Tool Characteristics (hereafter DTCs) for analysing and comparing Digital Sketching with Traditional Sketching and CAD is created to tackle the first research question.

As mentioned above, the importance of building a comprehensive framework of DTCs for this study is knowing the affordances of Digital Sketching and drawing comparisons with its neighbouring tools (Traditional Sketching and CAD Modelling). In terms of the creation of the Design Tool Characteristics (DTCs) framework, a detailed literature review is conducted. Two major relevant frameworks for analysing design tools are identified and discussed; namely, the Five Universal Tool Characteristics (UTCs) (Self, 2011), and the Five Characteristics of Sketching (Pei et al., 2011). Besides, more universal characteristics of design tools from the literature review are adapted individually into the new DTCs framework. The creation of the detailed DTCs framework, as well as the proposed theoretical DTCs of Digital Sketching based on literature, are described in Chapter 2.

The Selection and Use of a Tool Within the Design Process

To understand the use of a design tool, an investigation of the design phases where the tool is used is essential (Bouchard et al., 2006). In this study, the Early-Middle

phases of the industrial design process are revealed as the potential phases when Digital Sketching can be further utilised (after a review of similar studies on design tools and the design process).

According to Aspelund (2014), the design process explains the journey of the designer and the evolution of the design solution in a project. Even though the design process is complex and iterative (Lawson, 2006; Aspelund, 2014; Ullman, 2009; Pahl and Beitz, 2013; Roozenburg and Eekels, 1995), a well-defined design process model could still guide a basic path of the journey and explain the expectations on designers and design tools during different phases. It stands to reason that the potential use of Digital Sketching during the industrial design process can be revealed by mapping the Design Tool Characteristics of this tool with the expectations during the design process. To understand which Design Tool Characteristics can influence industrial designers' selection and use of Digital Sketching during the design process in practice, a detailed description of a well-accepted industrial design process model would be beneficial to contextualise the study.

Similar studies on the selection and use of Digital Sketching and its neighbouring tools focus on the earlier phases of the design process. Various terms of these phases are used by researchers in different 3D design fields; i.e., "creative design/process" (Shih et al., 2015; Robertson and Radcliffe, 2009; Nagai and Noguchi, 2003), "conceptual design/stage" (Mustafa, 2013; Dorta, 2007; Lipson and Shpitalni, 2000), or "the early stage" (Haggman et al., 2015; Knight et al., 2005; Yang and Cham, 2007; Lin et al., 2008; Tang, 2002). However, a more comprehensive description of those phase(s), regarding both the designer's activities and the design outcomes, is needed for determining what motivates and reflects the selection and use of a design tool. Hence, a working model of the industrial design process which includes specific expectations of designers and visual representations is synthesised from existing literature in Chapter 3.

The literature review and its findings formed a basis that initialised the two core research questions of this study as follows.

Research Question 2: ***How does Digital Sketching manifest in industrial design practice during the Early-Middle design phases?***

Research Question 3: ***Could Digital Sketching be a "pathway" to ease transitions between Traditional Sketching and CAD in industrial design practice?***

In summary, a more comprehensive Design Tool Characteristics (DTCs) framework and a clear description of the Early-Middle industrial design phases are given after

the literature review and knowledge synthesis to set the foundation for exploring and understanding the use of Digital Sketching in practice.

Research Methodology

To answer the research questions, the research methods and methodology are further defined. The Design Research Methodology (DRM) is a well-established research approach which offers different types of methodologies to guide various types of design research and develop support for designers and researchers. The broad and general nature of the DRM framework helps to clarify the research path and guide the project progress without limiting the creativity design. The Type 3 research methodology of the DRM framework is adopted due to its suitability to conduct a study on design tools and the nature of PhD studies. Blessing and Chakrabarti (2009:18) illustrate the suitability of conducting a PhD project with this "Type 3" DRM; i.e., the general scale and depth of study, the time length of the project, the reliability of results etc. based on the nature of this project and the expectation of the research outcomes. This methodology framework is adopted to ensure the execution of the project can be efficient and the experimental design of the project can be effective.

To be specific, according to Blessing and Chakrabarti (2009)[61], the Type 3 DRM, a 4-stage research methodology, is usually used to conduct research projects: "When the understanding of the existing situation obtained from the literature review and reasoning is sufficient to start the development of support, a Comprehensive Prescriptive Study is undertaken if existing support is non-existent or insufficient". From a methodological point of view, this study could use the guide of the DRM to research both theoretical and practical uses of Digital Sketching in industrial design; hence, a more comprehensive understanding of this tool can be expected.

The "existing support" for Digital Sketching and its uses based on the literature review and reasoning seems to be insufficient to explain the current use of this tool in practice. From "existing support" sources in literature, the theoretical potential of more efficient and effective utilisation of Digital Sketching in Early-Middle design phases is revealed. The literature review results also suggest a gap between the use of Digital Sketching in theory and in design practice.

Therefore, to get a more comprehensive understanding of Digital Sketching, the "development of support" in this study is needed, which are investigations and experiments with practising designers in practice. Hence, as the "development of support", the Review-based Descriptive Study is followed by a "Comprehensive Prescriptive Study",

in which semi-structured interviews and unobtrusive observations with practising industrial/product designers are conducted.

The study is designed and conducted as follows:

- **Stage 1 Research Clarification**

  Objectives: Identify topics of interest; Select type of research; Raise research questions; Determine areas of relevance and contribution; and Formulate a research plan (Blessing and Chakrabarti, 2009)[44].

  Research Activities: Literature Review and Reasoning

  Based on literature review and reasoning, the use of Digital Sketching in industrial design practice is chosen as the topic for this study. The subsequent challenge posed for the project is to find an approach to understand and compare Digital Sketching with other design visualisation tools. This is described as research question 1, which will be resolved through the *review-based descriptive study I*. Core research questions of this project will be defined after the *review-based descriptive study I*. At the *research clarification* stage, the overall research methodology is chosen and a research plan is given. Areas of relevance are determined as design visualisation tools and their uses in practice, tool-use behaviours of designers, industrial design process and deliverables/expectations. Areas of contribution are determined as domain knowledge and industry implications regarding the use of Digital Sketching.

- **Stage 2 Review-based Descriptive Study I**

  Objectives: Develop an answer to research question 1; Understand the potential use of Digital Sketching in theory; and Draw overall conclusions based on the literature review (Blessing and Chakrabarti, 2009)[80-81].

  Research Activities: Literature Review and Reasoning

  A more comprehensive Design Tool Characteristics (DTCs) framework is created as an approach to conducting further investigation and is suggested as an answer to research question 1. Based on the literature review on Sketching, Digital Sketching and Design Tool Characteristics, and Industrial Design Process, the more effective and efficient potential use of Digital Sketching in the Early-Middle phases in industrial design process is indicated in theory. However, existing support for this potential from the literature is insufficient, and the current use of Digital Sketching in practice has been suggested as relatively limited and conservative compared to its neighbouring tools. This conflict, discovered in the literature (with limited data and support from practice/industry), suggests the necessity

to conduct a *comprehensive prescriptive study* on the use of Digital Sketching in industrial design with the DTCs framework, especially to develop more data and support on the patterns of use and applications of Digital Sketching in industrial design practice.

- **Stage 3 Comprehensive Prescriptive Study**

  Objectives: Obtain and analyse support to answer the core research questions 2 and 3, mainly to understand the manifestation of Digital Sketching during the Early-Middle phases in the industrial design process versus its neighbouring tools in practice. Manifestation is defined as the patterns of use and applications of Digital Sketching by practising industrial designers.

  Research Activities: Data collection from the semi-structured interview and observation studies with industrial design practitioners, and data analysis on the results.

  Using the characteristics from the Design Tool Characteristics (DTCs) framework, data regarding the use of Digital Sketching and its neighbouring tools in industrial design practice collected from the semi-structured interview and observation studies with practising designers are coded. Results from the interview and observations formed the basis to picture the manifestation of Digital Sketching in practice versus Traditional Sketching and CAD. The results suggest the more effective and efficient use of Digital Sketching in the Early-Middle phases in industrial design process can be expected, and the reasons are explained by its DTCs. Similarly, the potential of using Digital Sketching to ease the troublesome transitions between its neighbouring tools can be discussed based on the experiment results.

- **Stage 4 Initial Descriptive Study II**

  Objectives: Indicate the applicability and usability (usefulness) of the results from the *comprehensive prescriptive study* (interview and observation studies); Indicate the issues, factors and links that need detailed evaluation; Suggest future research plans.

  Research Activities: Reasoning.

  The applicability and usability (usefulness) of the results are discussed. The answer to research question 1 is further discussed concerning the usability of the DTCs framework as an approach to analyse and compare design visualisation tools based on the outcomes from the *comprehensive prescriptive study*. Answers to core research questions 2 and 3 are concluded with noted limitations. The overall reliability and limitations of the study are also analysed. Future work and research are suggested and recommended.

With the guidance of the chosen research methodology, a more detailed overview of the project and the thesis is given in the following section.

Project and Thesis Overview

The specific research plan and the thesis structure are given in Figure 4 as research clarification. At first, the overview of Sketching and Digital Sketching offers a general understanding of the use of Sketching in design. A narrative description of Digital Sketching regarding its affordances is summarised based on the literature reviewed. Some of the affordances are inherited from the general nature of sketching and digital media, the others are unique. The description indicates the not yet fully utilised potential of Digital Sketching in design practice. Hence, it formed the research problem and initialised the first research question.

Three research questions are proposed in total in this study to understand and explore the use of Digital Sketching in industrial design practice. Research question 1 is a stepping stone that mainly focuses on resolving how to understand and compare Digital Sketching with other design visualisation tools to enable further investigations of this tool, and the answer leads to the creation of the Design Tool Characteristics (DTCs) framework. The core research questions are research questions 2 and 3, which are formalised in Chapter 4 after the *Review-based Descriptive Study I*.

The three research questions and objectives are:

1. How to compare Digital Sketching with other design visualisation tools?

    - Identify the most common neighbouring tools of Digital Sketching.
    - Understand the target and potential design phases for Digital Sketching to achieve its potentials.
    - Build a detailed framework for conducting comparisons of design visualisation tools.

2. How does Digital Sketching manifest in industrial design practice during the Early-Middle design phases?

    - Investigate the current use of Digital Sketching in industrial design practice.
    - Explain the reasons behind the limited use of Digital Sketching in practice.

- Reflect on the strengths and limitations of Digital Sketching in comparison with its neighbouring tools.

3. Could Digital Sketching be a "pathway" to ease transitions between Traditional Sketching and CAD in industrial design practice?

    - Explain the troublesome transitions between Traditional Sketching and CAD.
    - Explore the opportunity to solve some of the issues experienced with Traditional sketching and CAD Modelling using Digital Sketching.
    - Explain the limitations of using Digital Sketching in Early-Middle design phases in industrial design practice.

In Chapter 2, the universal comparable characteristics of design visualisation tools are proposed as an approach to understand and analyse design tools. A comprehensive Design Tool Characteristics (DTCs) framework is adapted and enriched from literature. The creation of this DTCs framework is regarded as an answer to research question 1 and part of the research outcomes of the project. The DTCs framework works as a basis to compare and analyse different design visualisation tools in industrial design. In this Chapter, the theoretical DTCs of Digital Sketching are proposed based on the description of its affordances created in Chapter 1.

A working industrial design process model is established to contextualise the study of Digital Sketching and its neighbouring tools in industrial design practice in Chapter 3. In this model, the general expectations on designers and design deliverables of different design phases are mapped to the expectations on the Design Tool Characteristics. Hence, the patterns of use of any design tool used in the industrial design process can be analysed and compared in terms of their DTCs. The theoretical use of Digital Sketching during the Early-Middle design phases is established after the syntheses of knowledge from the first three chapters, from which the gap between the use of Digital Sketching in theory and in industrial design practice is identified. At the same time, the transitions between its neighbouring tools, Traditional Sketching and CAD, are highlighted as something that could be troublesome for the designers. These findings lead to the core research questions 2 and 3 of the study.

Research question 2 is to understand the patterns of use and applications of Digital Sketching in industrial design practice. Relevant research activities are designed to gather more data to further discuss the gap between the use of this tool in theory and practice. Through interviews and observations with design practitioners, the "embodiment" of the tool within the day-to-day activities of designers is investigated and com-

pared with its neighbouring tools. Hence an answer to research question 2 can be discussed based on the data which shows what designers think and use when Digital Sketching in practice. The results also form a base to discuss the answer to research question 3, which is to explore the potential of using Digital Sketching to ease the troublesome transitions between its neighbouring tools based on the DTCs of these tools.

Chapter 4 firstly explains how these two core research questions are defined, and why, based on the findings from the review-based descriptive study I. Then it presents tangible research methods to answer these two questions. The twenty most relevant studies are highlighted as a base to search for effective methods to conduct the investigations. Semi-structured interviews and unobtrusive observations are suggested as research methods. Interviews with designers aim to reveal designers' understanding of Digital Sketching and its neighbouring tools. As supplementary data, unobtrusive observation is proposed as an approach to triangulate the interview results and offer deeper insights into the actual use of Digital Sketching based on designers' tool-use behaviours in different scenarios.

Another gap identified in the literature contributes to the selection of research methods; namely, the study of real-world design practitioners is less examined. This is particularly due to designer accessibility and the difficulties in structuring experiments in an industry setting. However, studying practising designers and their selections and usages of design visualisation tools in different scenarios is critical for this study to truly understand and explore the use of Digital Sketching in design practice. Gathering information from design practitioners on both perception and behaviour levels regarding the selection and use of design tools could add more value to the findings as this is lacking in relevant studies. The findings from the interviews and observations with design practitioners can help to reduce this gap in the literature and contribute to the domain knowledge.

Data collected from interviews and observations have been analysed separately in Chapter 5 and Chapter 6, which use the DTCs framework to identify those DTCs most frequently mentioned, and which can be considered as associated. This data indicates the characteristics of Digital Sketching (as it does with Traditional Sketching and CAD) that motivate its use and applications in practice. Hence, the manifestation of Digital Sketching can be further discussed.

The discussion of how Digital Sketching manifests, and thus the extent to which data answers research question 2, is given in Chapter 7. The discussion of manifestation is viewed from the perspective of effective design visualisation and efficiency within the design process. It is assumed that practising designers not only seek to create highly

effective visual communication but also to do so in a time (and hence budget) efficient manner. Thus, discussion in Chapter 7 also explores how the frequently mentioned DTCs of Digital Sketching and its neighbouring tools explain the use and applications of the tool to deliver effective visualisation in a time efficient manner. The understanding of its manifestation also facilitates a reflection on how the tool is used and applied in practice, which is the basis to answer research question 3. The comparison of their DTCs explains the usages and applications of the three tools and what motivates designers to employ them. Doing so could highlight any opportunities for Digital Sketching to bridge and smooth the transition between Traditional Sketching and CAD as described by DTCs which motivate tool use. To summarise, the answers to both research questions 2 and 3 are discussed with the experimental results in Chapter 7.

In conclusion, a more comprehensive and up-to-date understanding of Digital Sketching and its patterns of use and applications in industrial design practice is provided, based on an experiment with practising designers. It forms the main contribution to domain knowledge in the study. Using the DTCs framework to understand and explore the use of Digital Sketching establishes an effective basis to provide rationalised insights into how it might affect the time efficiency of design processes and outcomes in practice.

The major outcome of the project; namely, an explanation of the strengths and opportunities surrounding the use of Digital Sketching in practice could promote more customised uses of Digital Sketching and offer advice on design tool development. The potential of using Digital Sketching to ease the troublesome transitions occurring during the Early-Middle industrial design phases is discussed. It offers a clearer explanation of the "comparative" strengths and limitations of Digital Sketching that could further guide the uses of this tool.

Future work and research inspired by this project is also recommended in Chapter 8.

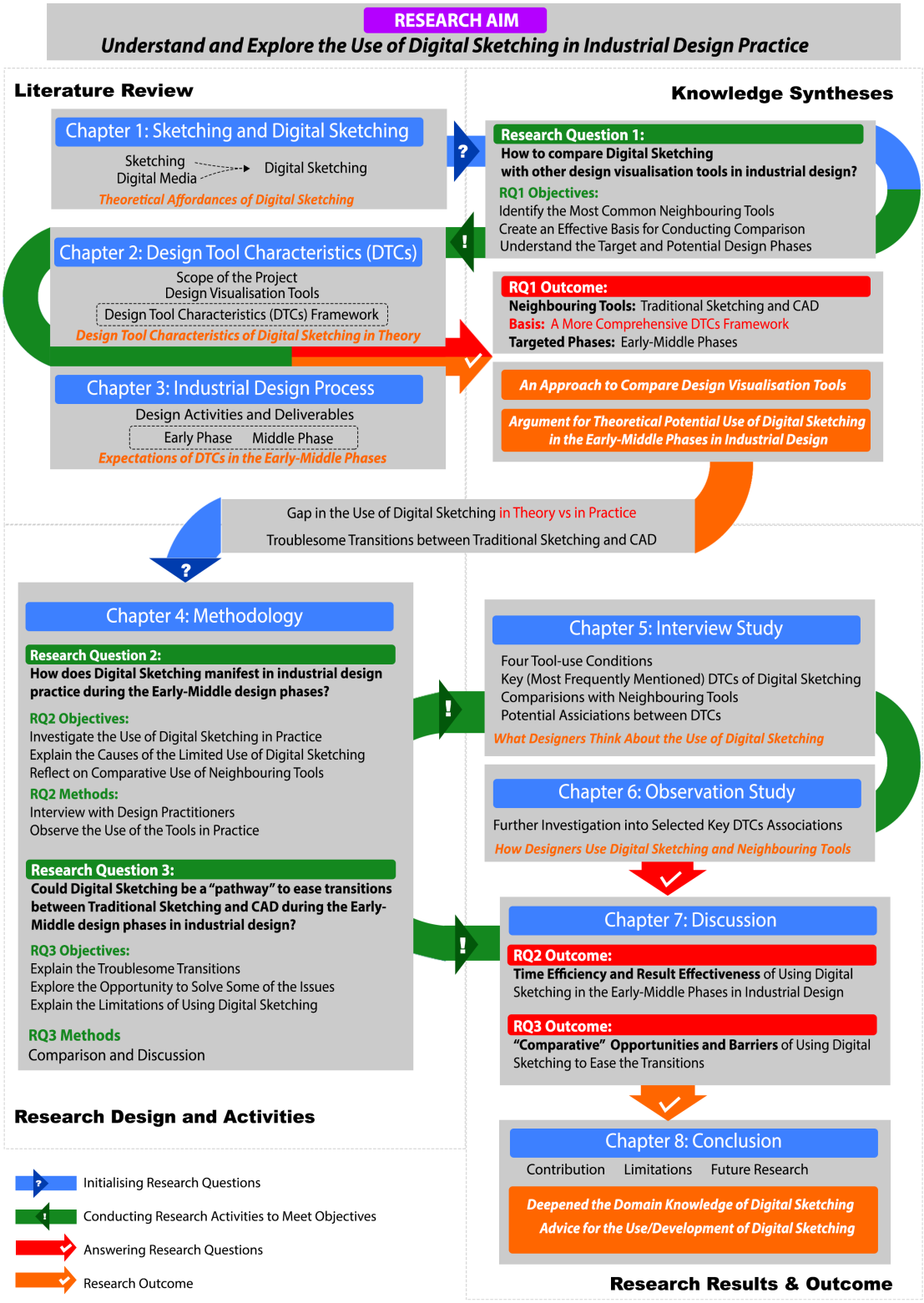


Fig. 4 Research Phases and Thesis Structure

CHAPTER 1

SKETCHING AND DIGITAL SKETCHING

This part of the literature review provides an overview of Sketching and Digital Sketching from definitions to up-to-date techniques. From education and industry perspectives, the value of using Digital Sketching in design, and its role and characteristics are reviewed and discussed in this chapter. The benefits, concerns and potentials of applying Digital Sketching in design practice are established from theory. The review indicates that Digital Sketching has affordances that could benefit designers in design practice. However, the general knowledge and awareness of this tool among designers might not be sufficient to utilise its full potential, and limited and conservative ways of using Digital Sketching can be seen in practice. As such, an up-to-date understanding of Digital Sketching would contribute to both domain knowledge and design practice. At the end of this chapter, a literature-based description of the affordances of Digital Sketching is proposed.

1.1 Sketching from Arts to Design

Sketching, a term derived from Greek "skedios", which means "done extempore", is a kind of rapidly executed drawing that usually intends unfinished work (White, 1990). Sketching has been serving artists and designers as a common activity to represent their direct precepts or ideas for centuries (Goldschmidt, 1991). Specifically, artists always use Sketching as a fundamental tool to start an art project, so Sketching is also a prescribed part of art student studies (Bleiweiss, 2012). Artists can sketch with various drawing mediums; e.g., pencil, charcoal, pastel, pen-ink, brush-watercolour and even oil. However, no matter what medium is used, the rough, unfinished feature in these sketches is still obvious.

The "unfinished" feature of Sketching reveals the secret of its utility. Aspelund (2014) states that the "unfinished object is pregnant with information". The first examples of

Sketching in design occur in *De Ingenisis*, a four-volume set of books on technology created in the 15th century by Mariano di Jacobi detto Taccola (McGee, 2004). McGee (2004) notes that Books 1–2 of *De Ingenisis* are filled with unfinished drawings, and this rough Sketching style provided Taccola with a graphic means of idea exploration. Buxton (2010) appraises that those unfinished drawings are the first examples of using Sketching to work through a design, and he notes that Sketching has also been the archetypal activity of design. In architectural design, the use of Sketching in the development and construction of buildings has a long history. For instance, Figure 1.1 displays the facade of Strasbourg Cathedral from the 1260s, and is one of the earliest surviving architectural sketches. It demonstrates the architect's uncompleted design idea of the west facade. Likewise, some famous sketches of Leonardo da Vinci show the use of Sketching in Engineering and Product Design in history. In Figure 1.2, the processes of creating a water lifting device and an automobile are presented with sketches.

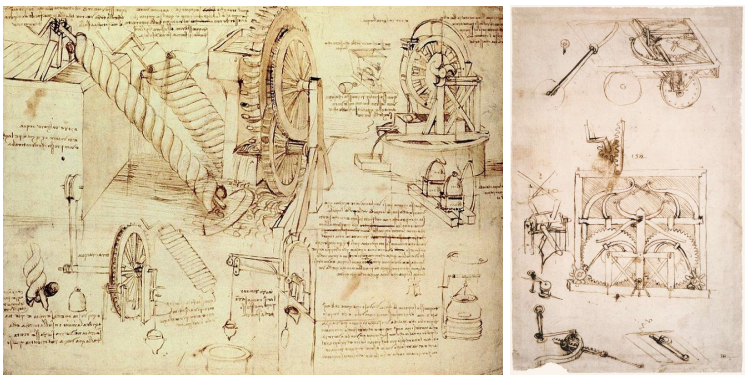


Fig. 1.1 Left: Facade of Strasbourg Cathedral Photograph by Notre-Dame, 1260s (Museum, 2009)

Fig. 1.2 Right: Water Lifting Device and Automobile by Leonardo da Vinci (LeonardoDaVinci.net, 2011)

The "unfinished" feature of these sketches is clearly different from painting or delicate drawing, and they offer the freedom and space for imagination and reinterpretation. According to Fish and Scrivener (1990), "Leonardo da Vinci advocated the use of untidy indeterminacies for working out composition because he believed that they stimulated visual invention".

Thus, one fundamental reason and purpose for using Sketching in design is revealed; namely, the freedom of reflective thinking gained from the stimulative "unfinished" visualisation.

1.2 Sketching and Design

In different design disciplines, Sketching has been used as a primary tool to assist the thinking process and create design representations by the majority of designers during the early phases of the design process (Aldoy and Evans, 2011; Pipes, 2007; Menezes and Lawson, 2006; Goldschmidt, 1991; Cross and Roy, 1989). According to the literature reviewed, the reason behind this phenomenon could be that the nature of Sketching offers designers a quick, intuitive way to discover, develop and solve design problems. Johnson et al. (2009) describe Sketching as a thinking and visual representing process. Similarly, Vistisen (2015) more recently proposes visual thinking and communication as the two research perspectives on Sketching in design practice and theory. So the discussion of Sketching in the next two subsections is developed from these two perspectives: its role in the thinking process and in design visualisation.

1.2.1 Sketching and the Thinking Process

A review of the literature indicates that Sketching supports designers' thinking process in two ways; namely, **generating ideas** and **conducting self-dialogue** (Linsey et al., 2011; Ullman et al., 1990; Nagai and Noguchi, 2003). In other words, Sketching assists the thinking process by **developing initial concepts** and **inspiring alternative ideas**.

Specific to the capability of Sketching in generating ideas, Chen (2007) notes that designers are able to quickly define and understand the design problem and to frame early ideas by Sketching. According to Johnson et al. (2009) and Brade et al. (2013), Sketching can support problem-framing and exploring possible solutions. Since sketches have affordable "disposability" (Buxton, 2010), then using Sketching as a tool for ideation could help designers keep exploring new ideas by throwing away previous unwelcome ideas on sketches (Strebel, 2017). Also, Sketching is useful for designers to "offload" their concepts (Romer et al., 2000), especially during complex design activity. Thus, many researchers agree with the ability of Sketching in provoking designers' creativity by developing and enriching their initial ideas (Cross and Roy, 1989; Tovey, 1989; Suwa et al., 1998; Schon and Wiggins, 1992; Do et al., 2000).

Since the thinking process of developing and enriching ideas is iterative rather than linear, Goldschmidt (1991) argues that Sketching also helps designers to conduct self-dialogue, which represents a reasoning modality of constructing continuing dialogues between "seeing that" and "seeing as". According to Goldschmidt (1991), the process of Sketching is a continuous production of displays pregnant with clues for vi-

sual reasoning. Likewise, Fish and Scrivener (1990) suggest that Sketching can assist "the descriptive-to-depictive translation process" of designers, "a one-to-many mapping intrinsic to inventive thought". In other words, this nature of Sketching aids the re-interpretation of ideas generated beforehand; that is, evaluating, verifying and generating design alternatives (Schon and Wiggins, 1992; Suwa et al., 2000; McGee, 2004; Van der Lugt, 2005; Olofsson and Sjolen, 2005; Bilda et al., 2006).

1.2.2 Sketching and Design Visualisation

Some researchers address the use of Sketching for **concept externalisation** and **communication** in design (Schon and Wiggins, 1992; Lawson, 2006; Goldschmidt, 2007). Bilda et al. (2006) demonstrate that Sketching can quickly bring ideas to concrete forms. Strebel (2017) also reminds us, in his video of a design project, that design ideas do not make sense before they have actually been drawn. Moreover, Evans and Aldoy (2016) and Tovey et al. (2003) agree that the high speed and spontaneity of Sketching are essential for concept externalisation.

Similarly, Purcell and Gero (1998) regard sketches as "the formation of images that provide a starting point related to a possible physical form and a way of developing that form". In order to better understand Sketching, Purcell and Gero (1998) also summarise five common characteristics of sketches: ambiguity, reinterpretation, knowledge generation, cyclic process and expertise-related. Moreover, the high capabilities of Sketching in storing and comparing thoughts are examined by researches (Bilda et al., 2006; Lawson, 2002).

In addition, the processes and outcomes of using Sketching also facilitate collaboration and communication in design (Goldschmidt, 2007; Yang, 2009; Pei et al., 2011; Evans and Aldoy, 2016). Or, as Crismond (2012) observes, Sketching is helpful in "enabling problem scoping and solution archiving by enhancing collaboration and communication". Hence, these capabilities of Sketching make it a significant design visualisation tool for designers.

1.2.3 Types of Sketching in Design

Since the types of Sketching vary considerably, educators and researchers started categorising Sketching according to the different design disciplines, Sketching outcomes or design purposes it served (Olofsson and Sjolen, 2005; Ferguson, 1994). For example, Xu (2015), an industrial design lecturer, categorises Sketching into three simple types

with recommended time consumptions based on practical purposes at his design studio for design undergraduates. According to the studio report (Xu, 2015), these practice-oriented types of Sketching are:

- Ideation Sketching: Usually takes 5–10 minutes;
- Communication Sketching: Usually takes 20–30 minutes; and
- Presentation Sketching: Usually takes 1–2 hours.

As in education practice, these types of category could give students a good basic understanding of the role of Sketching in design project and practice before they start focusing on pure skill training (Xu, 2015).

As in academia, McGown et al. (1998) label five categories of sketches in engineering design based on the physical elements and detail levels. Olofsson and Sjolen (2005) summarise four functions of Sketching in design: investigative function, explorative function, explanatory function and persuasive function. Later, Pei et al. (2011) propose a more detailed framework of visual design representations that includes eight types of Sketching, where the four main categories of sketches in industrial design process are:

- *Personal Sketches*: which can be sub-categorised into Idea Sketch, Study Sketch, Referential Sketch and Memory Sketch;
- *Shared Sketches*: which include Coded Sketch and Information Sketch;
- *Persuasive Sketches*: namely, Sketch Rendering; and
- *Handover Sketches*: namely, Prescriptive Sketch.

These four Sketching types also indicate different uses of Sketching in design processes. By building an analogy between the categories of Pei et al. (2011) and Xu (2015), the role of Sketching in design becomes relatively clear: **A tool for conducting both the thinking process and design visualisation.** As is in Table 1.1, the types of sketches mentioned by Pei et al. (2011) and Xu (2015) are grouped by their focuses on supporting the thinking process and visualisation. The different types of sketches in design also reflect their different roles in design processes.

Thinking Process	Thinking and Visualisation	Visualisation
Personal Sketches Ideation Sketch	Shared Sketches Communication Sketch	Persuasive Sketches Handover Sketches Presentation Sketch

Table 1.1 Table of the Use of Different Types of Sketches in Design as Defined by Pei et al. (2011) and Xu (2015)

1.2.4 Discussions on the Role of Sketching in Design

Many researchers agree that Sketching and design activities seem inseparable (Buxton, 2010; Yang, 2009; McGown et al., 1998; Tovey, 1989), and that Sketching helps designers create better design outcomes (Yang, 2009; Song and Agogino, 2004; Schütze et al., 2003). In contrast, some other researchers argue that Sketching might not be so necessary or adequate in certain design scenarios.

Specifically, an investigation of Bilda et al. (2006) shows that the use of Sketching has no direct influence on the quality of design outcomes for design experts. Yang and Cham (2007) claim that there are no direct links between Sketching skills and design outcomes in engineering design, and that "sketches are only one avenue for designers to represent their thinking". In this particular research, they debate that "'good' sketchers did not necessarily do well on the project or vice versa" by mainly examining the total sketch quantity and project grade of participants.

Further, Ibrahim and Rahimian (2010) note that manual Sketching is not an efficient tool to use in globalised design projects. This case also outlines the potential limits in our understanding of Sketching if we intuitively refer to Sketching as pen-paper based Traditional Sketching. As a typical example, Jonson (2005) debates the primary use of Sketching in the design ideation process based on his investigation of Traditional Sketching, words description, model making and computing.

However, the media currently used in Sketching varies a lot from traditional pen-and-paper to the digital environment, even with Virtual Reality (VR), due to the ongoing digitalisation in design (Chandrasegaran et al., 2013; Alcaide-Marzal et al., 2013). One particular case is the use of different types of digital graphic tablets for design Sketching; such tablets include Wacom/Ugee/Huion-branded digital tablets with or without built-in display screens (Amazon, 1996-2017; Ebay, 1995-2017).

Not only professional graphic tablets but also portable smart devices with pen-like inputs have been used as digital graphic tablets for Sketching; e.g., iPad and Microsoft

Surface Pro. Another new digital platform for Sketching in design is Cross-Reality (XR), specifically Virtual Reality (VR) or Augmented Reality (AR). An example is Gravity Sketch, an application that allows designers to create immersive 3D design sketches in a VR environment as demonstrated in Figure 1.3.

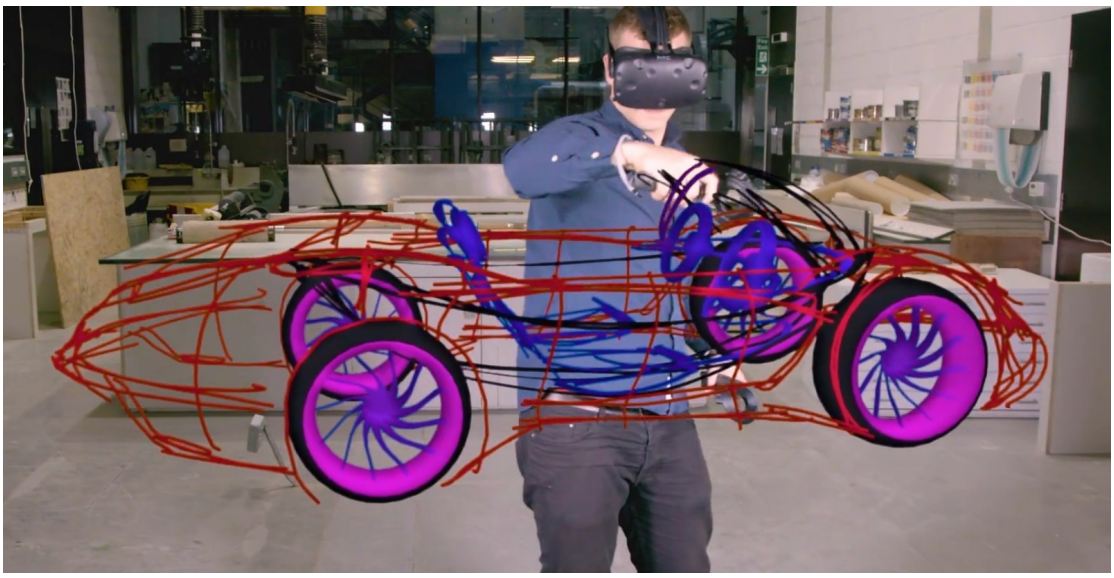


Fig. 1.3 A Designer is Creating a 3D Digital Sketch (GravitySketch, 2014)

From the discussion above, it is safe to propose that digital media and digital techniques can influence design Sketching in many aspects. In this study, in order to include the digital side of Sketching in the design for further investigations, a working definition of Sketching follows.

Sketching is a category of tools that offers an intuitive and quick connection between designers' thinking process and visualisation, and it is not limited to Traditional Sketching based on pen and paper that could include Digital Sketching. The use of Sketching does not always aim for or end with a finalised or completed version of the design solution (Song and Agogino, 2004; McKim, 1972).

Hence Digital Sketching, the next focus of this literature review, can be seen as a subcategory of Sketching, which is built upon digital media.

1.3 Digital Sketching: Sketching with Digital Media

Recently, Digital Sketching – Sketching with digital media – is emerging in design practice and is also arousing interest in academia (Alcaide-Marzal et al., 2013; Aldoy and Evans, 2011; Evans and Aldoy, 2016; Shin, 2009). This section presents some

affordances of Digital Sketching inherited from both digital media and Sketching as a resultant combination of both. Other identified affordances of Digital Sketching from literature are also described in this section. Firstly, the use of digital media in design is reviewed to provide an understanding of its influence on Digital Sketching. Stereotype impressions or uses of Digital Sketching in design are noted from the literature. Then the role of Digital Sketching, relevant technologies, and the theoretical benefits and concerns of using it in design are discussed to attempt an explanation of general stereotype impressions.

1.3.1 Digital Media in Design

As Shin (2009) states: "As the scope and applications of design technology grow, designers are relying more and more on computers to aid in the design process." The use of Digital Sketching in design practice also raises concerns about the relationship between digital media and creativity (Stones and Cassidy, 2010; Haggman et al., 2015; Aish, 1977).

Digital media can be defined as any media that is encoded in a machine-readable format, which can be created, viewed, distributed, modified and preserved on digital electronic devices. In general, creativity involves two significant aspects of design: new and valuable. Creativity is defined as the production of items which are novel and useful (Mumford, 2003) or original and worthwhile (Sternberg and Sternberg, 2016). The concerns of digital media in design mainly come from its influences on the creative design process. As Abdelhameed (2004) notes: "The trend of digitalization in media use throughout the design process affects visual thinking performed in design-exploration tasks."

Some researchers note that the changes caused by digital media in design knowledge base and design process (Oxman, 2008; Liu and Lim, 2006; Sass and Oxman, 2006) also challenge design education. As Oxman (2008) states: "Existing models of architectural education are in the process of adjustment to new cultural and technological conditions of the digital age." Oxman (2008) concludes that "there will be a need to educate a new generation of digital design specialists". Also, Shin (2009) addresses the necessity of "ensuring that design practitioners and students understand the potentials of these new technologies and are adequately prepared to utilize them".

Therefore, before fully applying digital media in any design process or practice, it is important to understand its potentials and the consequences. This knowledge can improve the efficiency of design activities and the utilisation of design resources.

1.3.2 Benefits of Applying Digital Media in Design

Researchers in different design disciplines agree that there are many benefits from using digital media in design (Lawson, 2002; Chen, 2007; Shih et al., 2015). Even back in the 1990s, researchers noticed that the improved control offered by computer software could be utilised in visualising design ideas – as Fish and Scrivener (1990) state: "Raster graphics software allows the user to directly manipulate the bit-map corresponding to this image." In other words, one of the benefits of applying digital media in design is that **the resolution and complexity** of design representations can be improved to pixel level (Mari, 2006; Shih, 2006).

The computer commands and software features could also **simplify and speed up the process of modifying design**, which is difficult to achieve with traditional media (Ranscombe and Bissett-Johnson, 2017; Evans and Aldoy, 2016; Ibrahim and Rahimian, 2010; Dorta et al., 2008); that is, undo, redo, copy, paste, duplicate, zoom in and out, resize, colour panels and layer functions. Moreover, Sketching and CAD can be further integrated with digital media and hence facilitate a smoother transition between 2D and 3D in the design process. For example, Ban and Hyun (2020) suggest that synthesised sketch-CAD workflow in digital space can "provide more design inspiration than traditional design methods" and "could be useful in the early design phase". Hence, the feasibility of a total digital design process also comes into the discussion. For example, Shih et al. (2015) state: "CAD modelling has proved to be effective across the whole range of architecture, engineering and construction practices... it can be used by itself from beginning to end to achieve design goals." Similarly, a study from Aldoy and Evans (2011) reveals that design experts have positive attitudes toward the concept of a total digital design process. On the contrary, the same study shows that students tend to have a relatively negative attitude of a total digital design process (Aldoy and Evans, 2011). Another benefit of applying digital media is that it can potentially **facilitate communication and collaboration even on a global scale** (Munson, 2004). More online design communities and online design projects are emerging with a digital communication environment and digitalised design outcomes. For instance, design tools based on digital and cloud design platforms (e.g. Onshape online CAD in Figure 1.4) offer designers in location-distributed design teams or international design organisations the opportunity to sketch, brainstorm or build 3D models together.

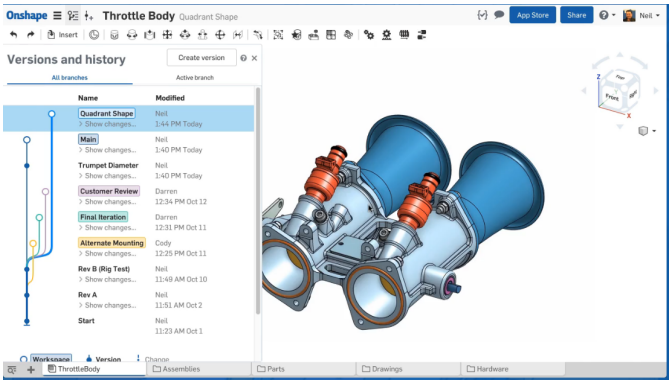


Fig. 1.4 A Full-cloud CAD Platform Offers Built-in Collaboration for Designers (Inc., 2019)

1.3.3 Concerns About Applying Digital Media in Design

However, there are also some concerns about the relationship between digital media and creativity. For instance, the discussion about CAD and creativity has been addressed for some time in academia. Lawson (2002) outlines the question "Does the computer really help?" by showing the difference between how designers think and how the software works in an architectural design case. Similarly, Dorta (2007) questions the use of computers in making better designs in a research of hybrid ideation tools, but at the same time he admires the benefits gained from computers. According to the experimental data, Won (2001) suggests that the computer may be useful in the creation of new solutions through its ability to provide **rapid transformations**. Conversely, Stones and Cassidy (2010) and Goel (1995) claim the process of reinterpretation is better supported in traditional media. One of the main concerns is the **premature design fixation** and the limited creative problem-solving process influenced by the early use of digital media, especially CAD modelling (Booth et al., 2016; Lawson, 2002; Robertson and Radcliffe, 2009; Yang, 2005). Bilda and Demirkan (2003) conclude that the use of digital media constraining designers' creativity could be caused by designers' already developed Sketching abilities and the inadequacy of CAD tools.

In addition, because designers have the tendency to be **immersed in the visualisation** or rendering process with digital design tools, Lawson (2002) argues that the use of digital media encourages "**convincing computer presentations with poor design**". Hence, he addresses the necessity to research the effects of CAD on design. The effects and causes of applying digital media to design are still not fully explored, while the use of digital tools (CAD and Digital Sketching) in design practice is simultaneously increasing.

1.4 Digital Sketching in Design

Compared to studies on CAD, studies on the effects of using Digital Sketching in design are even fewer in number. For the benefits of design education and industry, it is vital to know what Digital Sketching is and how it should be used. However, to define Digital Sketching in a more specific way seems relatively difficult. Some researchers emphasise the use of digital tablets when they research Digital Sketching (Evans and Aldoy, 2016), while some others refer to Digital Sketching as a kind of representation by using computer-based 2D graphics software (Stones and Cassidy, 2010; Knight et al., 2005). From the literature on digital design and media, the lack of a universally agreed definition of Digital Sketching can be caused by, but is not limited to, two main reasons:

1. The advanced technologies embedded in Digital Sketching are continuously developing, therefore its definition cannot be associated with a specific media or technology.

2. The role of Digital Sketching in the design process is not yet as certain as traditional tools.

1.4.1 Digital Sketching Technology – A History Through to Present

Different from Traditional Sketching, Digital Sketching is involved with new media and advanced contemporary techniques – specifically, various software and hardware. One of the first graphics tablets was created by the RAND Corporation in the early 1960s (Davis and Ellis, 1964), which depended on Ivan Sutherland's research of the 2D Digital Sketching system "Sketchpad" (Sutherland, 1964). Digital technology has been developing on a global scope and at high speed within the last 30 years. Hilbert and López (2011) state that telecommunication has been dominated by digital technologies since 1990, and the majority of our technological memory has been in digital format since the early 2000s. Consequently, the technical development of Digital Sketching has become more advanced since the creation of the RAND Tablet "Grafacon" in the 1960s.

The types of Digital Sketching hardware can be categorised into **2D and 3D devices** in terms of the working environment of Sketching activity. 3D Digital Sketching hardware now, like Gravity Sketch, usually requires AR and VR techniques, haptic systems, or at least behaviour tracking techniques (Alcaide-Marzal et al., 2013). Meanwhile,

2D Digital Sketching hardware is based on digital devices that support pen-like input and graphic output; i.e., digital graphic tablets, iPads and Microsoft Surface Pros. In addition, digital tablets with embedded touch display screens simulate the pen-paper working environment better than traditional digital tablets. For instance, in Figure 1.5, Wacom Cintiq 27QHD Touch can make the Sketching process more **natural and intuitive by supporting synchronous hand-eye coordination** than traditional tablets without display screens like the Wacom Bamboo. Similar to Wacom Cintiq, other manufacturers also offer commercial graphic tablet-screen hybrids (e.g. GT-series from Huion, UG-Series from Ugee, Tooya series from PenPower, SenTIP from Hanvon, and more).

Fig. 1.5 A Designer is Sketching With a Cintiq 27QHD Touch (Wacom, 2019)

Similarly, we can categorise Digital Sketching software into **2D and 3D software** products. According to the literature (Eissen and Steur, 2007; Olofsson and Sjolen, 2005) and a market survey, the most commonly used 2D Sketching software in PCs are Adobe Photoshop, Autodesk Sketchbook, Corel Painter, Adobe Illustrator and software offered by digital tablet suppliers. More than the broad benefits from digital media mentioned above, there are a few common features in 2D Sketching software that help designers to develop their ideas. Firstly, the various types of software usually support **mouse input and pen-like input** from digital tablets or touch-screens, which can **simulate the real freehand Sketching experience.** Additionally, they offer **options of tools and functions** which largely extend the capability of Traditional Sketching; namely, several Sketching tools from pencils, brushes to textures, and other features such as multilayers, colour panels, effects, filters, templates, libraries and so on (Adobe, 2017). As an illustration, Marx (2000) proposes that an almost infinite number of independent layers “can

be moved and manipulated without affecting other layers, and can be edited in a number of ways, always preserving the ability to change back to a previous version". Thus, the layers feature also **helps the completion or annotation** of design representations (Eiliat and Pusca, 2013). Another very helpful feature for novice users is the "symmetry axis" that can **save a lot of time and effort to create more accurate** symmetric shapes by setting a horizontal or vertical axis in SketchBook software (Chou-Tac, 2015). Similar to the layers and the symmetry axis features, other useful attributes improve the capabilities of Digital Sketching in many ways. Additional innovative 2D Sketching applications for iOS and Android operating systems, which are **portable on mobile devices**, have been introduced to designers: Autodesk Sketchbook, Tayasui Sketches Pro, Paper by FiftyThree, Sketch Master and so on. Figure 1.6 shows that these mobile applications also share similar features with 2D Sketching software on PCs.

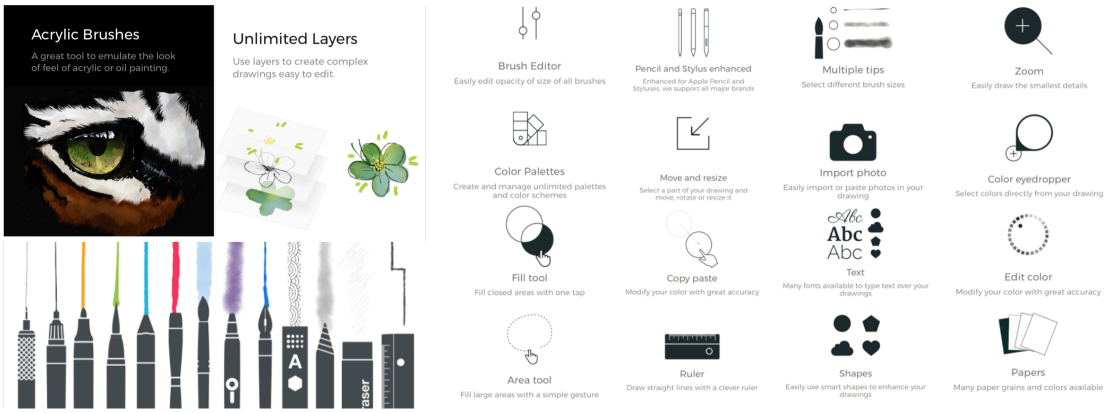


Fig. 1.6 Features of Tayasui Sketches Pro (Tayasui, 2019)

Most 3D Digital Sketching software products are based on 3D reconstructions from stroke or shading recognition techniques; animation and game designers usually use them for character design. For example, MARI – a digital 3D painting and texturing software for character design used by many animation and film design studios – provides an analogous toolkit for 3D painting (Mari, 2006). Other 3D software products that allow designers to develop 3D digital mock-ups should be considered; e.g., ZBrush, Mudbox and 3D Coat. Further, researches have been performed on 3D sketches for product and engineering design. Alcaide-Marzal et al. (2013) state that the 3D sculpt sketching system should be "a sketch based modelling system, a CAD system capable of dealing with 2D hand-sketched curves and transforming them into 3D editable volumes".

In summary, all of these software and hardware products – which are important components of Digital Sketching – update and change rapidly with the development of technology. Meanwhile, the academic literature on Digital Sketching is limited; thus, it

is difficult to define Digital Sketching in an up-to-date and precise way.

1.4.2 The Role of Digital Sketching in Design

The other difficulty in defining Digital Sketching is that its role has been naturally regarded as just a digital mimic of Traditional Sketching instead of an independent design tool which needs an in-depth understanding on its own. Even in textbooks on Sketching, the concept and use of Digital Sketching are also relatively limited in this way. Olofsson and Sjolen (2005) note that digital software aids Sketching in creating a new media which is "often used on scanned hand-drawn line art, to add separate layers of colours and effects". Similarly, Eissen and Steur (2012) mention the use of graphic software and digital tablet as a **rendering step of Traditional Sketching** or a way to build up a presentation in many illustrated design cases.

In some design research, Digital Sketching is overlooked when analysing the role of Sketching in design. For example, Shih et al. (2015) compare Sketching and CAD design environments without mentioning Digital Sketching. From working experience and the supplementary support from online investigation, many designers and design students use Digital Sketching as a sketch-rendering tool to present better-looking sketches or to bridge the gap between Traditional Sketching and CAD in design practice. As in a product design video (Strebel, 2017), solutions of the design problem have been explored by the designer with Traditional Sketching, then rendered and tweaked with Digital Sketching software. To use Digital Sketching as a tool for **refinement/rendering before using CAD Modelling** has been regarded as a "standard" process in many design cases. In other words, Digital Sketching has been principally viewed as an alternative to paper-based techniques; a digital environment that mimics Traditional Sketching, a way to render scanned traditional sketches (Eissen and Steur, 2007, 2012; Olofsson and Sjolen, 2005); or a bridge between paper-based sketches and 3D CAD models (Evans and Aldoy, 2016; Tang et al., 2011). However, the role of Digital Sketching in the design process could be more complex than a digital mimic of Traditional Sketching with its software features and hardware techniques.

Therefore, the potential role of Digital Sketching in the design process might have been underestimated due to its less recognised status and characteristics.

1.4.3 Benefits and Concerns About Applying Digital Sketching in Design

Since Traditional Sketching is likely to require more accurate manual operations than Digital Sketching, an investigation of an online sketch blog (Chou-Tac, 2015) suggests that many students complain about their frustrations when using pen and paper. Comments on the sketching tutorial page (Chou-Tac, 2015), like "struggled with perspectives and visualising objects", "became very stagnate" after years of practising, "unable to draw", or "no confidence to pen down", indicate that this frustration is a general feeling shared among design students. Given the physical capabilities of Digital Sketching mentioned in Subsection 1.3.2 and Subsection 1.4.1, this technology could help to **ease or dismiss students' frustration** and to **improve their focus on the "real design"**, which means that Digital Sketching could also influence the creative process of designers. Some research results illustrate the benefits of applying it in the design process. Compared with Traditional Sketching in traditional media, Digital Sketching could **lower the "Sunk Cost"** (Viswanathan and Linsey, 2011) of changing and developing concepts for designers, based on the availability of various sketching tools, and could also offer new possibilities for design representations. For instance, Madrazo (1999) and Marx (2000) agree that digital visual representations can support visual thinking by offering **a better understanding of the form and frequently giving immediate feedback**. Moreover, the digital representation of initial design ideas can also **promote communication and collaboration in a much wider scope** than the early design stages, which could also help the thinking process of designers by embracing more stimulations from others. For example, Figure 1.7 shows the community/gallery/showcase feature that applies in some 2D apps for Digital Sketching, and also provides more chances for designers to get their designs exposed and have online conversations with others.

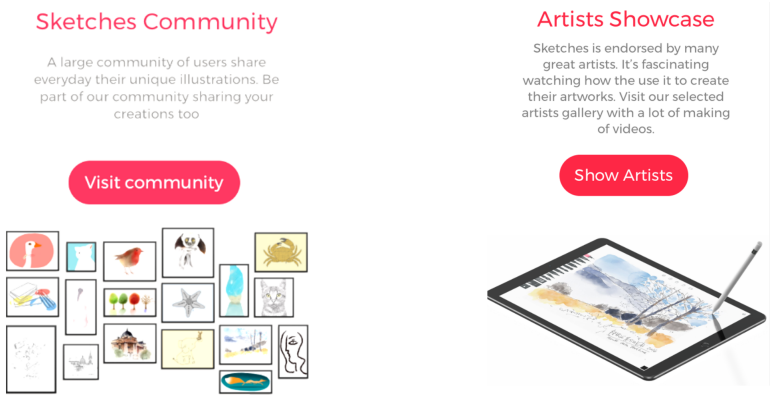


Fig. 1.7 Sketches Community and Artists Showcase (Tayasui, 2019)

Studies by Knight et al. (2005) indicate an increased willingness among designers to

value the digital representation, and the once elevated value of traditional representations is no longer necessarily held. As Eissen and Steur (2007) notes in a design case shown in Figure 1.8, the subtle yet effective material properties created by the use of digital watercolour technique "give the drawings a highly realistic appearance". It seems that **the aesthetic attractiveness** of digital sketches could be relatively higher than Traditional Sketching. Consequently, this more attractive representation style may make design ideas more persuasive, but the good or bad influence of its **persuasive** characteristic depends on its use in context. Specifically, a timely persuasive representation of a well-developed idea can promote the whole design process, while a persuasive representation of a premature idea can freeze the development of ideas (Aspelund, 2014:108) and terminate the creative activity prematurely. In addition to this potential problem, Aspelund (2014) also proposes that designers could create impossible things with Digital Sketching or modelling software because "everything on screen seems much more possible than hand sketch".

Fig. 1.8 Primatist G70 Leisure Speed Boat (Eissen and Steur, 2007)

According to Prensky (2001), one general concern of the digital age in the education field is the new process of thinking and analysing information. Concerns about applying Digital Sketching in design also focus on its impact on creativity. Similar to the downside of its more persuasive representation style, designers could be tempted towards endless revising and fixing images due to **the control flexibility of software and the high clarity of representation** when they should be focusing on idea-exploring (Aspelund, 2014). From the literature, some researchers compare the influences of Digital Sketching and Traditional Sketching on creativity. For a considerable period, Traditional Sketching has mostly been regarded as the medium of thought processes while Digital Sketching is claimed not to be supporting creativity (Bilda and Demirkan, 2003; Verstijnen et al., 1998; Van Elsas and Vergeest, 1998). As a typical example,

Goel (1995) argues that experienced designers are more active in reinterpretation when they are using Traditional Sketching instead of Digital Sketching within constrained software. Similarly, Stones and Cassidy (2007, 2010) state that the use of Traditional Sketching generates more concepts and solutions than digital working in graphic design. It seems the cognitive process of using Traditional Sketching results in higher creativity; for example, Fish and Scrivener (1990) state that the understanding of that mental process could help to improve computer sketching systems. So, to properly examine the effects of using Digital Sketching, the cognitive processes of designers and design students in both Traditional Sketching and Digital Sketching should be analysed.

In a study regarding the capacity of tablet PCs to support Digital Sketching during industrial product design activity, Evans and Aldoy (2016) explain that people questioned the benefits of applying Digital Sketching because of certain Digital Sketching hardware products. They state in this research that those products with small screens that **prevent the viewing of other ideas** can devastate the process of idea exploration. Therefore, the research of Digital Sketching must consider the software and hardware products involved as well.

1.5 Chapter Summary

In this chapter, the theoretical potential of Digital Sketching in design, and its stereotypical impression as a mimic tool for beautifying paper-based traditional sketches in general, are both reviewed from the literature. It could be difficult for academic researchers, design educators, students and designers to realise the capability of Digital Sketching – and utilise it accordingly – due to a lack of in-depth understanding. Hence, this chapter aims at giving an in-depth theoretical understanding of Digital Sketching in design as a basis to further explore its use in practice. Theoretically, Digital Sketching might help to generate more alternative ideas, efficiently obtain more accurate feedback, and offer a friendlier user experience to the designers. The structure of Chapter 1 is summarised in Figure 1.9.

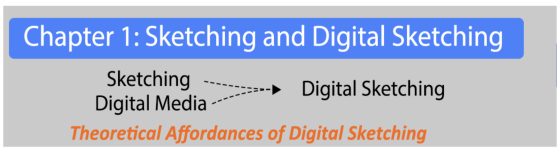


Fig. 1.9 The Structure of Chapter 1

At first, Sketching in design is categorised into Traditional Sketching and Digital Sketching. The working definition of Sketching itself in this study is a broader category that

is not limited to any media form. By reviewing the role that Sketching plays in the thinking process and in design visualisation, four general Sketching characteristics are revealed, which are likely to be inheritable for both Traditional Sketching and Digital Sketching. As Digital Sketching is involved with the use of digital media, the benefits and concerns of applying digital media in design are reviewed. The power of digital media confirms that there is further potential in Digital Sketching that needs to be unfolded to the design community to change their limited and conservative current use of Digital Sketching in practice. Also, an overview of Digital Sketching in the field of design is given to reveal its unique affordances. A summary of both the inherited and unique affordances of Digital Sketching is shown in Table 1.2.

Affordances of Digital Sketching	**Sources**
Generating Ideas Inspiring Alternatives Externalisation Enable Communication	Inherited from Sketching in Design
Pixel Level of Control Improved Resolution and Complexity Simplify and Speed up Modification Rapid Transformation Global Scale Communication and Collaboration Risk of Premature Fixation Risk of Immersion in Visualisation	Inherited from Digital Media in Design
Easy 2D to 3D Considerable Intuitive Eye-Hand Coordination Mouse Input and Freehand Simulation Low Sunk Cost Multiple Built-in Tools High Accuracy Low Cost of Time and Effort Portable Devices Considerable Low-Learning Frustration Better Understanding of Forms Persuasive and High Aesthetic Attractiveness Immediate Visual Feedback Online Community Risk of Limited View Size	Self-developed Unique

Table 1.2 Table of the Identified Descriptions of Digital Sketching

In summary, Digital Sketching nowadays progresses with technology developments and

has a greater potential role in the design process. The theoretical affordances of Digital Sketching are revealed from the literature. However, a more comprehensive understanding of Digital Sketching needs an in-depth investigation of its affordances, including its comparative strengths and limitations compared to other design visualisation tools. Hence, it initialises the first research question in this study to find an effective basis to compare Digital Sketching with other design visualisation tools. The first research question of the study is formally introduced in Chapter 2 after the scope of the investigation is further defined. Briefly, an approach to compare design visualisation tools is required that generalises their different affordances to comparable universal factors.

CHAPTER 2

DESIGN TOOL CHARACTERISTICS AND DIGITAL SKETCHING

To have a more comprehensive understanding of Digital Sketching, comparisons between Digital Sketching and other design visualisation tools are critical. Research question 1 in this study is described as *how to compare Digital Sketching with other design visualisation tools in industrial design*. Even though the scope of this study is refined down to the industrial design field, a review of relevant studies on basic design representations in 3D design fields, including industrial design, is used to provide a broader understanding of the use of design visualisation tools. Design Tool Characteristics (hereafter DTCs) are suggested by the literature as a potential approach to investigating and evaluating design visualisation tools. A more comprehensive framework of DTCs is created based on a review of the design tools in 3D fields to address research question 1. With the framework, the theoretical affordances of Digital Sketching listed in Chapter 1 are interpreted and rationalised as the theoretical DTCs of Digital Sketching in this chapter.

2.1 Design Visualisation Tools and Digital Sketching

According to McCullough (1998), tools are actively used by human beings for specific purposes as extensions of themselves. For designers, the purpose of using design visualisation tools is to communicate and deliver design solutions from their brains to the physical world (Goel, 1995; Self, 2011). Lutters et al. (2014) report the selection of tools during design activity as mostly relying on the designers' expertise and creativity, and using tools can improve the way of doing designs. Also, designers use an expanding inventory of design tools during their design practice (Pipes, 2007; Self, 2011; Goel, 1995). It follows that the more we know about a design tool, the greater chance to figure out its real potential and make better use of it in design practice.

To evaluate Digital Sketching, comparisons with its comparable or neighbouring design tools hence show that its comparative strengths and limitations are essential. Therefore, to define the main comparable and neighbouring design tools of Digital Sketching, a literature review on design representations in relevant 3D design fields and on design visualisation tools in industrial design is conducted. A working category of basic design visualisation tools in industrial design is built as a guideline for making comparisons.

2.1.1 Research Question 1 and the Review-based Descriptive Study I

Research question 1 of the study and the following objectives are defined as the first step to investigate the use of Digital Sketching. Based on the literature review, an effective approach or basis to understand or compare Digital Sketching, as well as other design visualisation tools in industrial design, is needed for an in-depth research outcome. Research question 1 aims to address this identified problem, and its following objectives are used to guide the research activities. Research question 1, its objectives, and where the research activities are outlined in the thesis are described as follows.

Research Question 1: How to compare Digital Sketching with other design visualisation tools in industrial design?

- Identify the most common neighbouring tools of Digital Sketching (Chapter 2)
- Build a detailed framework for conducting comparisons of design visualisation tools (Chapter 2)
- Understand the target and potential design phases for Digital Sketching to achieve its potentials (Chapter 3)

As described in the Design Research Methodology (DRM), the research method used to collect data for this research question is literature review and reasoning. Hence, the Review-based Descriptive Study I stage starts from this chapter. A summary of the outcome of this stage is given in Chapter 4, where the other two core research questions are defined. The final discussion and conclusion of the research questions, including research question 1, are in Chapters 7 and 8.

2.1.2 Basic Design Representations in 3D Design Fields

In order to research the use of design visualisation tools, different types of resulting outcomes from applying these tools in practice – design representations – are reviewed

in this subsection. Extant literature shows studies defining design representations using various taxonomic methods in 3D design fields.

Lawrence (1993) states that fundamental design representations in the field of architectural design include sketches, drawings, words, models and computer-aided modelling and drafting kits, etc. A taxonomy of design representations in industrial design from Pei et al. (2011), also known as IDSA cards, lists 32 types of design representations in industrial design from 2D idea sketch, presentation rendering, appearance model, to final hardware prototype.

Table 2.1 shows the different types of design representations grouped by their dimensional differences based on this taxonomic classification of visual design representations in industrial design and engineering design (Pei et al., 2011). In other words, Pei et al. (2011) indicate that design representations in industrial design and engineering design fields could be grouped as 2D and 3D design representations. At the same time, the transition from 2D representations to 3D representations in 3D design fields (including industrial design) is also noted from the literature.

2D Visual Design Representations		**3D Visual Design Representations**	
Group	Sub-group	Group	Sub-group
Sketches	Personal Sketches Shared Sketches Persuasive Sketches Handover Sketches	Models	Industrial Design Models Engineering Design Models
Drawings	Industrial Design Drawings Engineering Design Drawings	Prototypes	Industrial Design Prototypes Engineering Design Prototypes

Table 2.1 Table of the Hierarchy of Groups in Pei et al. (2011)'s Classification

In the following subsection, the design visualisation tools that are used to generate the design representations in industrial design are reviewed in the same manner, namely 2D or 3D design visualisation tools.

2.1.3 A Working Category of Design Visualisation Tools in Industrial Design

According to a taxonomy of Self et al. (2009), there are eleven fundamental types of design visualisation tools from sketching tools to model-making tools in industrial design. Based on the literature review, a working category of design visualisation tools in industrial design is proposed as shown in Table 2.2.

The sub-categories of **Sketching** can be listed as Traditional Sketching and Digital Sketching to make a distinction between the two tools as discussed in Chapter 1.

Similarly, **Modelling** could be categorised into Traditional Modelling and Digital Modelling. Based on preliminary observations in practice, Traditional Modelling includes Modular Physical Modelling, Semi-Modular Physical Modelling and Freestyle Physical Modelling. Specific physical modelling design tools, like LEGO blocks that are made of modular units, can be regarded as Modular Physical Modelling tools. The use of LEGO in design has been developed for some time (Crismond, 2012), and designers can use LEGO to quickly build abstract but tangible models to represent their ideas. Semi-Modular is a concept built from the comparison with Modular Physical Modelling, which means the materials used have more plasticity than modular units. The Semi-Modular Physical Modelling tools commonly used in design practice are paper, cardboard, timber plates, etc. Freestyle Physical Modelling tools could be more intuition friendly for designers, and they usually refer to the use of clay, foam and other soft sculpting materials. Virtual Modelling mainly refers to various CAD software products. Even some 3D CAD modelling tools have both surface modelling and solid modelling features, the subcategories of Virtual Modelling are still classified by these two features. As a general domain knowledge, Surface Modelling is also known as free-form surfacing, which means building 3D models by describing their surface and curves, while Solid Modelling means building 3D models by combining a set of 3D solids.

Similarly, the sub-categories of **Prototyping** are defined by the traditional and digital media used. Meanwhile, sub-categories of **Rendering** are defined by the dimensional format of the representations that are imported into rendering tools; i.e., 2D rendering and 3D rendering.

Since the context of further analysis on Digital Sketching is clarified as industrial design, this working category of design visualisation tools lists the potential design tools that are suitable for making comparisons with Digital Sketching. To be specific, Digital Sketching and Traditional Sketching both fall under the category of Sketching, and the use of Digital Sketching in industrial design practice usually comes after Traditional Sketching. Digital Modelling, referred to as CAD in this study, is chosen over Traditional Modelling as the other comparable neighbouring tool due to the shared digital media. The use of CAD after Digital Sketching and Traditional Sketching is general practice in the industry. Based on the literature review, the main comparable design tools of Digital Sketching in industrial design are determined by its neighbouring tools, namely Traditional Sketching and CAD Modelling.

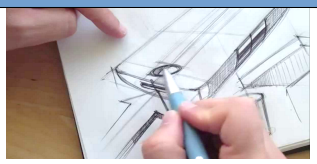
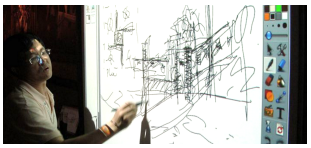
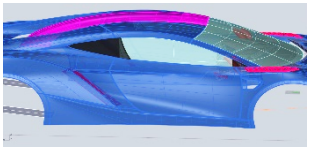
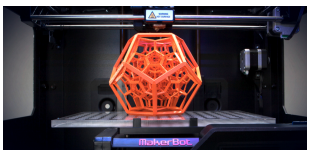
Category	Sub-category	Examples
•**Sketching**	Traditional Sketching	
	Digital Sketching	
•**Modelling**	Traditional Modelling	
	Digital Modelling	
•**Prototyping**	Traditional Prototyping	
	Digital Prototyping	
•**Rendering**	2D Rendering	
	3D Rendering	

Table 2.2 Table of a Working Category of Fundamental Design Tools in Industrial Design

2.2 Characteristics of Design Tools

As Lutters et al. (2014) state, characteristics of techniques and tools are more efficient, credible and useful in capturing the essence of tools than collecting endless lists of existing tools. Therefore, the goal of this section of this review is to identify the comparable characteristics, which are termed as Design Tool Characteristics (DTCs) in this context, for this study. DTCs can be used to describe a design tool by breaking down its entire personality to analysable factors. To systematically analyse and evaluate design tools, some researchers built frameworks of DTCs. For specific research purposes, these previously built frameworks of the DTCs list and highlight some characteristics. In this section, two selected frameworks, which share a similar research purpose with this project, are reviewed.

2.2.1 Previous Frameworks of Design Tool Characteristics

Self's Five Universal Tool Characteristics (UTCs)
In this first example, Self et al. (2009) propose a framework named the Five Universal Tool Characteristics, which describes five common characteristics to investigate when analysing the capabilities of design tools in supporting designers to conduct design activities. According to Self (2011), the five identified universal characteristics of design tools are termed:

- **Mode of Communication**: The modes of communication include communicating design ideas via self-reflection to oneself (Lawson, 2006, Goldschmidt, 1991) as well as communicating design intentions via design embodiments to others (Self, 2011), which could also be seen as the internal communication and external communication of design ideas.
- **Level of Ambiguity**: The extent of ambiguity to which design tools support design representations is a common characteristic that has been identified for some time, and has been mentioned in published researches regarding sketching and comparison studies concerned with sketching versus other tools (Brereton, 2004; Goel, 1995; Stones and Cassidy, 2010; Goldschmidt, 1991; Alcaide-Marzal et al., 2013; Booth et al., 2016). The level of ambiguity in design representations, which also represents the level of abstraction, could affect the effectiveness of design ideation/conceptualisation processes (Cross, 1999; Goel, 1995; Brereton, 2004). In other words, it could affect both the process of perceiving visual information and the emergence of ideas.

- **Transformational Ability**: The transformations of thinking occurring in design can be categorised into lateral and vertical transformations, and shifts between these transformations could also happen during the design process (Goel, 1995). According to Self (2011), the *lateral transformation* is the movement from one idea to a new idea, while the *vertical transformation* is working on variations of the same idea. Both of these transformation activities are essential for design practice. Additionally, according to Visser (2010), there are more detailed types of transformations; namely, duplicate, add, detail, concretise, modify and revolutionise.

- **Level of Detail**: In this framework, Self (2011) refers to the level of detail as degrees of specificity in design representations as well as the amounts and display modes of information. Self (2011) also notes the difference between the Level of Detail and the Level of Ambiguity in that the Level of Detail "describes the embodiment of more or less specific information" while the Level of Ambiguity is used to denote opaqueness of ideas or concepts.

- **Level of Commitment**: As Self (2011) states, the Level of Commitment describes that design ideas may be perceived closer to or further away from completion by clients or stakeholders, in terms of requirements for manufacture. Since different types of visual representations may indicate different Levels of Commitment, this characteristic could be misleading and unwanted if tools are used at relatively inappropriate design stages (Pipes, 2007; Self, 2011).

Purcell and Gero's Five Characteristics of Sketching

In this second framework example, by narrowing the research scope to sketching, Purcell and Gero (1998) summarise five "themes" regarding the nature of sketching, which also reveal five inter-related characteristics of sketching (Alcaide-Marzal et al., 2013).

- **Reinterpretation**: This characteristic of sketching is similar to the "Lateral Transformation" (Goel, 1995) of **Transformation Ability** in Self's work at page 43, and it refers to the emergence of new ways to interpret drawn representations into design ideas. In addition, Purcell and Gero (1998) state that the reinterpretation characteristic is also referred as "Seeing as" actions (Goldschmidt, 1991), "Moves" between representations and new ideas (Schon and Wiggins, 1992) or "Focus Shifts" (Suwa et al., 1998).

- **Denseness and Ambiguity**: The concept of denseness and ambiguity in sketching has been referenced in the item **Ambiguity** of Self's framework at page 42. Also, Purcell and Gero (1998) emphasise that the ambiguity characteristic of sketching results in reinterpretation.

- **New Knowledge/Information**: As Purcell and Gero (1998) state, the concept of the new knowledge characteristic can be referred as the "Seeing that" action (Goldschmidt, 1991). When designers are using sketching, this continuing perception/generation of new information, including both new perceptual and conceptual knowledge, also becomes part of the problem-solving process. In other words, it could potentially affect the thinking process as well as design outcomes to a considerable extent.

- **Cyclic Process**: The Cyclic Process represents the dialectic movements from reinterpretation and generation of new knowledge to further reinterpretation addressed and access to new knowledge during the use of sketching tools in design. Additionally, Purcell and Gero (1998) note that "the bringing in of new knowledge, brought about by reinterpretation, is a process that progressively reduces the ill-defined nature of design problems".

- **Level of Expertise Related**: Since the types and amounts of individual knowledge vary considerably, the issue of expertise is significant regarding the use of sketching in design. According to Purcell and Gero (1998), the Level of Expertise Related characteristic influences designers, not only in their use of tools but also in terms of their cognitive activities. Therefore, the expertise related characteristic of design tools is one of the most important characteristics to analyse their capability to improve creativity.

2.2.2 Similarities and Differences of the Two Frameworks

As discussed above, these two frameworks of tool characteristics in design indicate a similar fundamental way of understanding and analysing design tools as well as designers and design activities.

Ambiguity is highlighted in both frameworks, but the investigation scope of Purcell and Gero (1998)'s Five Characteristics of Sketching is obviously more specific than the scope of Self's Five Universal Tool Characteristics (UTCs). Another difference between the two frameworks is the purposes for which they are built for. The Five Universal Tool Characteristics (UTCs) framework condenses some broadly shared characteristics of design tools into five essential ones for revealing and analysing designers' attitudes towards the tools (Self, 2011:112). In other words, the resulting framework is built from the perspective of design tools' properties/capabilities and their relationship with designers.

Differently, the five characteristics of sketching are identified in terms of the use of

sketching during the design process according to Purcell and Gero (1998). Besides, the five characteristics are highly interlinked. The characteristic of **Level of Expertise Related** is noteworthy, because it reveals a very important perspective to analysis design tools: the users/designers. Since the framework is built for analysing the capability of sketching on improving creativity, the effects on tools from designers are necessary and significant to consider.

The two frameworks are chosen for discussion as they are relevant to this study in terms of research topic and intent, to research the way designer's engage with design tools. They illustrate the utility of tool characteristic frameworks as a basis to analyse design visualisation tools in the industrial design field. Moreover, among existing frameworks of design tool characteristics, they are both relatively highly cited and have been employed by other similar studies (Evans and Aldoy, 2016; Lutters et al., 2014; Robertson and Radcliffe, 2009; Jonson, 2005). Furthermore, the two frameworks show some similarity to one another, which also provides further validation of characteristics that are included as they can be cross-referenced before being added to a more comprehensive Design Tool Characteristics (DTCs) framework in this study. Finally, the two frameworks also indicate two important perspectives of investigating the characteristics; namely, the tools' capabilities and those of the users. Beginning from these two frameworks, more characteristics of design tools are identified through the literature review within relevant 3D design fields to ensure a more comprehensive DTCs can be developed.

2.3 Understanding Digital Sketching: Creation of the Adapted Design Tool Characteristics (DTCs) Framework

The relevant design fields reviewed in this chapter are 3D design fields that have similar tool-sets to industrial design, including architectural design, interior design, urban design, product design (Lawson, 2006) and engineering design. Similar to the goals of both frameworks mentioned above, a well-built DTCs is necessary for better understanding digital sketching in the context of three-dimensional design disciplines. The frameworks above have already built a foundation for analysing design tools and the relationship between designers and the tools, but there are more characteristics identified through the literature review that could/should be taken into account. In many studies, researchers intentionally or unintentionally mentioned some "less obvious" characteristics of various design tools. In this section, these characteristics, as well as some characteristics that overlap with the above frameworks, are identified and termed.

2.3.1 Identified Capability-related Characteristics of Design Tools (CCs)

Similar to the perspective of Five Universal Tool Characteristics (UTCs) (Self, 2011), characteristics listed in this subsection, which are identified from the perspective of tools' capabilities, could help to reveal the potential of design tools in terms of their facility to support designers. In other words, differing from the characteristics that were identified from the perspective of the tool users (designers), the focus of the Capability-related Characteristics of Design Tools (CCs) is on the intrinsic properties of both design tools and the design representations created with those tools.

- **Ambiguity**: This characteristic of design tools has been identified by many studies for some time as illustrated on page 42. The Ambiguity of Design Tool Characteristics refers to "the extent of ambiguous and unambiguous representation of ideas" (Self et al., 2009) that tools can support. It is the vagueness that causes multiple interpretations to happen. By regarding design representations as symbolic systems characterised by syntactic and semantic denseness (Goel, 1995), the extent of ambiguity or the denseness in design representations could increase because of syntactic disjointness/differentiation and semantic disjointness/differentiation, which might potentially lead to more lateral transformations for design creativity (Goel, 1995; Tang et al., 2011).

- **Problem Re-framing**: Problem Re-framing happens when the use of certain design tools provides or supports an environment in which previous problem frames can re-emerge, be re-evaluated, combined and revised (Self and Pei, 2014). Therefore, different from **Internal Communication** that focuses on the solutions, Problem Re-framing means reconstructing the understanding of design problems which could lead to significant innovations. The characteristic of Problem Re-framing describes the extent of supporting Problem Re-framing activity that designers obtain from tool use.

- **Lateral Transformation**: When considering the potential differences of tools to support different types of transformations, the **Transformation Ability** mentioned on page 43 has also been broken down into two core characteristics. The Lateral Transformation, which is highly interlinked with **Ambiguity**, represents the horizontal movements of ideating and the breadth of ideas – or can be seen as the "generation of new ideas" (Alcaide-Marzal et al., 2013).

- **Vertical Transformation**: According to Goel (1995), the Vertical Transformation is the variation of the same idea when the **Lateral Transformation** is not sufficiently supported. Also, this characteristic is known as detailed development

or "Depth-first transformations" (Cross, 2001), where the occurrence frequency usually goes up during the design process.

- **Level of Commitment**: This characteristic is the same as the **Level of Commitment** in Self's UTCs framework that is mentioned in subsection 2.2.1.

- **Fidelity**: Fidelity here can be understood as the accuracy of communicating the inner ideas or the accuracy of the "Externalisation" (Self and Pei, 2014; Vistisen, 2015; Stones and Cassidy, 2010). Compared to the concept of **Level of Commitment**, this characteristic can also be seen as the level of self-commitment which represents "the degree of resemblance or accuracy of the medium to be able to represent/embody the designer's mental model or target concept" (Sauer and Sonderegger, 2009).

- **Accuracy**: Compared to **Fidelity**, this characteristic represents how precisely the objective mechanical/ dimensional information is supported by the design representations/tools.

- **Mobility**: This term could refer to the physical mobility of not only any specific design tool but also design representations created by it, and this characteristic is likely to affect the use of the tool. Some researchers refer to Mobility as "Portability" (Hoeben and Stappers, 2001; Evans and Aldoy, 2016), and Evans and Aldoy (2016) describe some differences of Mobility in terms of traditional sketching device versus digital sketching device. Generally, the mobility of digital representations is higher than paper-based representations or physical models in most design scenarios.

- **Immediacy**: The delay between the creative inspiration and digital representation has been noted by some researchers (Dorta et al., 2008; Aldoy, 2011). The characteristic identified from this discovery is termed Immediacy in this review, and it refers to the fluidity and continuity of the doing-displaying process when designers are using tools. It could help to reveal the relationship between creativity flow and the fluency/accuracy of feedback visualisation. Specifically, Tang (2002:61) also indicates the existence of this characteristic; he states that "sketches and their corresponding functional references were fast enough to catch up the speed of intention shift and thus the speed of thoughts". Evans and Aldoy (2016) also apply a similar concept referred to as "speed and spontaneity" when analysing the use of sketching. In addition to time-related Immediacy, cognitive Immediacy, in terms of intuitiveness, could also affect design creativity.

- **Flexibility**: The term of Flexibility refers to the freedom of changing and developing ideas with design tools. This characteristic is related to many aspects of

design tools, such as the material of the device, the interface, the capability to undo/erase/dispose of former representations (Buxton, 2010) and the number of steps to make changes or add details (Ranscombe et al., 2017). From the perspective of designers, Flexibility could be related to the "Sunk Cost" (Linsey et al., 2011; Viswanathan and Linsey, 2011), which means the extra non-functional investment of time or effort during the process of achieving a goal or solving a design problem. Viswanathan and Linsey (2011) describe that the higher the "Sunk Cost" is, the more unlikely the development/change of ideas. Therefore, the Flexibility, the supportiveness of making changes from design tools, is critical for design creativity.

- **Aesthetic Detail**: The concept of this characteristic is the same proposed by Self et al. (2009), and sketching is usually considered as the tool to create minimal detail (Buxton, 2010:111). According to the nature of industrial design, the level of detail is divided into Aesthetic Detail and Engineering Detail since different design tools are better at supporting one of them.

- **Engineering Detail**: Chen (2007) adds that the level of details also refers to the level of engineering and manufacturing information as well as the level of form detail-complexity represented.

- **Level of Aesthetics**: Visual aesthetics has been studied in the field of Human-Computer Interaction (HCI) for some time, especially in User Experience Design (UxD) (Tractinsky, 2012). The Level of Aesthetics characteristic here refers to the average beauty or the general emotional attractiveness of representation created with design tools, and it could be related to the style, type and number of representations. The Level of Aesthetics of representations could influence designers' way of both thinking and doing. For instance, the higher the level of aesthetics that a design representation has, then the higher possibility that a design idea will survive because of its attractiveness. Therefore, if the Level of Aesthetics of representations created with a design tool reaches a high level – by which we mean the high aesthetic appeal of the representations – then there appears to be a greater attraction to visualisation than to idea exploration. As Larsson (2016) discusses, the reason he prefers to use traditional sketching as an ideation tool is that the outcome of traditional sketching is usually messy while the outcome of digital sketching is much cleaner and tidier.

- **Amount of Representations**: Through the literature of Sketching, one characteristic that emerges is the Amount of Representations. Buxton (2010:111) states that sketches are usually plentiful, and the representations of ideas tend to exist in the context of a collection that could potentially stimulate design creativity. In

terms of the design tools reviewed, the quantity of representations and the way representations are distributed – that is, isolated or in a collection – could also be a significant DTC that needs to be considered.

- **Holistic View of Objects**: Tang (2002) states that "according to design situation, to view design in contextual level provokes novelty". Hence, if the provision of a Holistic View of Objects is available, which means designers could thoroughly view the current objects/representations created through the design tools used, then the more innovative and comprehensive the designs could potentially be. Also, the level of this characteristic might relate to the scalability and size of the interface (Brade et al., 2013); the working material of the tool/interface; and the Subjectively-Perceived and Objectively-Displayed Loading Time of the view, etc. Due to the working environment of the tool and its interface, the provision of a Holistic View of Objects in a virtual CAD representation could take much more time and effort than in a physical model in a small-scale three-dimensional design case. For example, in Figure 2.1 below, the holistic view, as well as other views of the physical model, could be more easily accessed by intuitive interacting with the object, while the CAD representation could only show one view at one time or per mouse drag. Shih (2006) states that the distance of a virtual world and a real world could be narrowed down in terms of design when the switch of views becomes more intuitive and continuous like a model on hand that can be viewed with visual depth directly. However, for example, if the scale of the design object is as large as a building, the situation is likely to be the opposite because accessing the Holistic View of Objects in a computer just takes a few mouse clicks or drags.

Fig. 2.1 Foam Model Mock-ups of a Handheld Product (7th London Ltd., 2014)

- **Compatibility**: Compatibility here refers to the capability of the outcomes gen-

erated with a design tool to ease the transitions in a design process. For the transition of media from physical to digital, the switch from Traditional Sketching to Digital Sketching is favourable and spontaneous (Strebel, 2017), which means the Compatibility of Digital Sketching towards Traditional Sketching is high. There are other transitions that could happen in a design process, such as the transition from 2D to 3D) and the transition from digital (layout) to physical prototype/production.

- **Use Cost**: According to the literature reviewed, the Use Cost can relate to the average time invested and cognitive demand of creating a self-satisfied or client-satisfied representation. Equally, the Use Cost could be divided into the time and mental efforts consumed. Bilda and Demirkan (2003) state that digital media could be time-consuming because designers have to deal with software attributes during design. At the same time, the "Sunk Cost" accrued during the design process can be lowered by the use of digital media; e.g., the undo function of digital design tools can save the effort of redrawing/remodelling/redesigning. Generally, the Use Cost of sketching has been estimated as lower than many other design tools as it is quick to generate and intuitive to make (Bilda and Demirkan, 2003). However, the general Use Cost of many design tools has not been fully investigated or noted according to the literature review. In addition, the specific Use Cost of a design tool during a design case could be varied according to the different levels of designer's experience or expertise and at different design stages. However, the necessity of generating and spreading the knowledge of the general Use Cost, which could improve the effectiveness and efficiency of the tool use, is relatively obvious.

- **Learning Cost**: Logically, compared to the **Use Cost**, we observed the Learning Cost. Also, this characteristic affects design in similar ways as does **Use Cost**. In other words, the Learning Cost characteristic refers to the general time invested and the cognitive demand in learning a design tool. This characteristic could potentially affect the selection of tools and the long-term loyalty of some design tools when designers/design students are doing designs. It could supposedly be changed by differing the learning materials, the timing or sequence of learning about tools, and the teaching methods, as well as environment settings. Therefore, to thoroughly evaluate a design tool and to create an "Effective Learning Experience" for design students, the analysis and study should take the Learning Cost into account.

2.3.2 Identified User-related Characteristics of Design Tools (UCs)

By considering the use of tools in design as a system, the variables for analysing the tools can be categorised into the tool itself and the user. So, different from the capability afforded by the tool itself – as discussed in the previous subsection 2.3.1 – the User-related Characteristics of Design Tools (UCs) here refers to the design tools characteristics that are related to the general use and user experience of the user/designer. A number of UCs are identified through the literature review, and are termed as follows:

- **Tendency to Switch Tools**: This characteristic describes designer's tendency to switch tools, which could be related to specific real-time design requirements as well as be interlinked with other CCs and UCs, namely, **Use Cost, Expertise, Accessibility**, etc. From research interviews regarding design or design tools, some types of this tendency have been mentioned as "had to go back to sketching" (Self, 2011); "switching from sketching to CAD modelling" (Shih et al., 2015); "changing media" (Chen, 2007); etc. This tendency from designers can lead to personal preference of certain tools, but sometimes the switching activity can also help improve creativity (Shih et al., 2015). Shih et al. (2015) state that switching between tools can facilitate designer's design processes and improve the quality of their design solutions. As an example, Strebel (2017) mentions that progress of the ideation process is made from the switch between sketching and building paper models. However, it is noteworthy that the activity of switching tools could also have a negative influence on design creativity due to the time, effort and/or financial costs.

- **Emotional Commitment to Ideas**: Emotional Commitment to Ideas refers to the attachment to existing ideas and the reluctance to change them (Mustafa, 2013; Self, 2011; Viswanathan and Linsey, 2011). When the Emotional Commitment to Ideas happens too early in a design process, it leads to the unwelcome phenomenon of premature "design fixation" (Crilly, 2015; Vasconcelos and Crilly, 2016). Even the Emotional Commitment to Ideas doesn't necessarily harm innovation when it occurs at the proper time, but it could still be an obstacle for continuing the creativity flow. This characteristic could be influenced by the **Lateral/Vertical Transformation, Ambiguity, Flexibility, Level of Aesthetics, Use Costs**, etc.

- **Expertise**: According to some investigations, designer's Expertise could change the way and the outcome of using design tools (Bilda et al., 2006; Menezes and Lawson, 2006). This characteristic also means the level of experience, skills and design knowledge that designers already have when they are applying design

tools. Vasconcelos (2016) emphasises the importance of looking into the relationship between the "expertise" of designers and the performance of designers. For example, Robertson and Radcliffe (2009) note that experienced designers are more likely not to be affected by circumscribed thinking when using CAD. Similarly, Yao et al. (2017) state that "novice designers are less skilled at framing new design problems but more capable of forgoing their initial design concepts". Moreover, the Expertise of designers could also be interpreted as the pre-mindset or "skill-set" (Booth et al., 2016) of designers, which could also potentially lead to design fixation (Crilly, 2015). Therefore, it is necessary to consider the effects from the Expertise of designers when analysing design tools.

- **Expectation**: This characteristic refers to the general expectation of the outcomes from designers when they are using certain design tools. For example, designers may feel the Expectation of showing more of their profession when using digital design tools because they feel more "formal" in the digital platform.

- **User Accessibility**: This characteristic means the general accessibility of design tools for design students/designers, which is potentially related to the purchase and maintenance costs of design tools as well as the **User Share** in market and industry. Also, the performance of designers using certain design tools is likely to be affected by this characteristic. According to a design student's comment on Wacom Cintiq (Personal communication 2017), his performance using digital sketching with tablets was poor because of the lack of access to the tool after class, and the purchase fee was too high to afford. So, the User Accessibility or the popularity of tools should be taken into consideration when evaluating design tools.

- **User Loyalty**: We have observed this characteristic from design practices in education and industry. The concept of User Loyalty is derived from "Customer Loyalty", but the User Loyalty of design tools refers to the attitudinal and behavioural tendency of designers to favour a design tool, not a commercial brand. It could be inter-related with other UCs, namely the **Tendency to Switch Tools** and the **Expertise** of designers. As an illustration, a heavy or extreme loyal user of traditional sketching might suffer greater difficulties on switching to or being engaged in digital sketching because of expertise.

- **User Share**: Similarly, User Share is a concept derived from "Market Share" in the business field, which means the percentage of users that a certain product has in the market. Hence, the design tools' User Share could be the percentage of users that own those tools in industry, education and even in different design

phases. Instead of directly influencing the use of design tools, this characteristic may have subtle effects on designers' minds, and it also indicates the tools' capability from the perspective of a user's practical selection. Besides, the User Share of certain tools in the industry can influence the selection of design tools in individuals and education. For example, if the local industry has a strong manufacturing sector and a high User Share of related design tools, the local design institution and students may prefer to focus more on those design tools than others.

2.3.3 The Adapted Design Tool Characteristics (DTCs) Framework

Through the literature review, more characteristics of design tools have been identified and discussed. In order to better analyse Digital Sketching, the new framework of the Design Tool Characteristics (DTCs) is established here, which can also be used for conducting studies on evaluating other design tools.

Using the system in Figure 2.2 below as a reference, the Capability-related Characteristics of Design Tools (CCs) are identified from the perspective of the inputs/effects that designers get from their use, while the User-related Characteristics of Design Tools (UCs) are identified from the perspective of designer's physical/mental inputs to the use of tools. However, as Figure 2.2 demonstrates, the designer's outputs could become or affect the inputs of the use of design tools. But also, inputs to the designer from the use of tools can affect the designer's next outputs. Therefore, the interaction between designer and the use of design tools suggests an interactive cyclic process. As, the adapted DTCs framework includes both the CCs and UCs as is shown in Table 2.3.

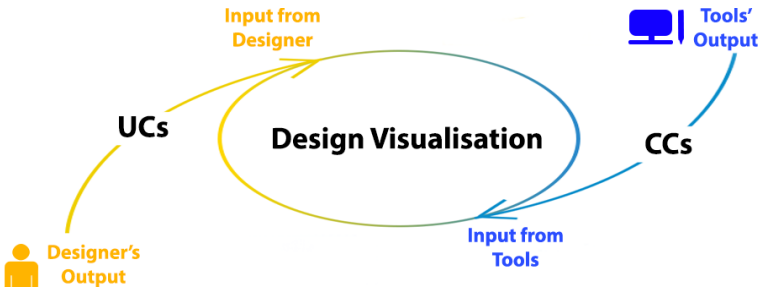


Fig. 2.2 The Interaction Between Designer and the Use of Design Tools

Design Tool Characteristics (DTCs)		
Capability-related Characteristics CCs)		User-related Characteristics (UCs)
Ambiguity	Immediacy	Tendency to Switch Tools
Internal Communication	Flexibility	Emotional Commitment to Ideas
External Communication	Mobility	Expectation
Externalisation	Engineering Detail	User Accessibility
Lateral Transformation	Aesthetic Detail	Expertise
Vertical Transformation	Holistic View of Objects	User Loyalty
Level of Commitment	Compatibility	User Share
Level of Aesthetics	Fidelity	
Accuracy	Learning Cost	
Problem Re-framing	Use Cost	
Amount of Representations		

Table 2.3 Table of the Design Tool Characteristics (DTCs)

2.4 Discussion: The DTCs of Digital Sketching in Theory

By applying the adapted framework of DTCs to Digital Sketching, the narrative description of Digital Sketching in Table 1.2 can be analysed more specifically. Quoted descriptions from Table 1.2 are in **bold** for quick reference.

- **Ambiguity**: Despite the stereotypical impression of Digital Sketching in that it is always associated with highly precise representations, Digital Sketching actually can generate representations with various levels of ambiguity.

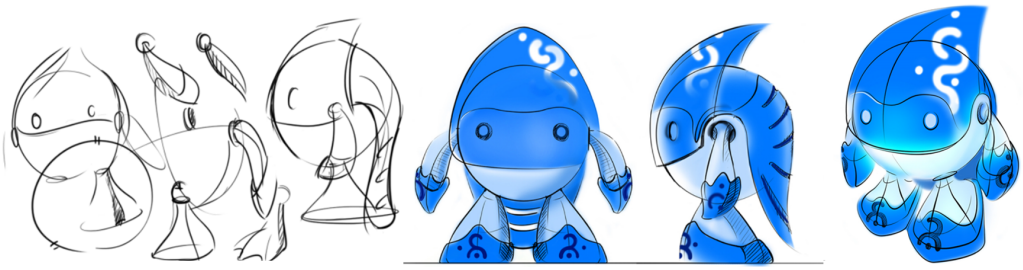


Fig. 2.3 Different Levels of Ambiguity in Digital Sketches

The pen-like input techniques and "softer" software products enable Digital Sketching to be used for creating ambiguous design representations which gives space for imagination and creativity (Stones and Cassidy, 2010). For example, Figure 2.3, created with Digital Sketching, represents the different levels of Ambiguity that Digital Sketching can easily attain.

- **Externalisation**: One of the inherited characteristics of Digital Sketching from Sketching is "**Externalisation**". With the "Considerable Intuitive Hand-Eye Coordination" and "Mouse Input and Freehand simulation", Digital Sketching should offer at least the same level of support for externalisation as Traditional Sketching. Moreover, the "**Pixel Level of Control**" allows designers to access potentially boundless possibilities (Stones and Cassidy, 2010).

- **Internal Communication**: As illustrated in Chapter 1, the use of digital sketches for External Communication is quite common for in-team communication.

- **External Communication**: Using Digital Sketching to communicate with clients is promising according to the literature. "**High Accuracy**" coupled with "**Persuasive and High Aesthetic Attractiveness**" make Digital Sketching a favourable tool for External Communication.

- **Problem Re-framing**: According to Self and Pei (2014), sketching helps designers with framing and re-framing design problems. As a subcategory of Sketching, Digital Sketching with a certain level of ambiguity (e.g. the high ambiguity digital sketches in Figure 2.3) could still support the happening of problem reframing. During the exploration of ideas, using Digital Sketching can trigger problem reframing by offering visualised potential solutions quickly, which can help designers restructure the design problems.

- **Lateral Transformation**: Since "**Generating Ideas**" and "**Inspiring Alternatives**" are inherited characteristics of Digital Sketching from Sketching, Digital Sketching should offer high support to conducting Lateral Transformation. However, the "**Risk of Premature Fixation**" from applying digital media might restrict Lateral Transformation to a certain degree. Some studies suggest that more alternatives can be generated by using Traditional Sketching (Won, 2001; Goel, 1995), but the scale of the studies needs to be considered (Stones and Cassidy, 2010), especially the low number of participants.

- **Vertical Transformation**: "**Better Understanding of Forms**", "**Risk of Immersion in Visualisation**", "**Improved Resolution and Complexity**" and "**Low Sunk Cost**" are the critical factors that give Digital Sketching high Vertical Transformation support.

- **Level of Commitment**: Design with Digital Sketching suffers the "**Risk of Premature Fixation**", which also represents a tendency towards commitment. Further, the attributes of "**Persuasive and High Aesthetic Attractiveness**" facilitate this tendency.

- **Fidelity**: "**Mouse-keyboard Input and Freehand Simulation**" of Digital Sketching ensure that the Fidelity of the digital sketches can be high. The freehand operation and other **built-in tools** of Digital Sketching ensure that design ideas with a curvy and organic look can be represented accurately (Stones and Cassidy, 2010). Meanwhile, mouse-keyboard input can help to define the dimensions and scale.

- **Accuracy**: Benefiting from the digital platform, the control accuracy of Digital Sketching can be managed with accurate digital input, which can offer higher Accuracy than freehand Traditional Sketching. Digital Sketching can provide "**Pixel Level of Control**" from digital media. For example, the scale of components can be set by typing specific numbers into the Digital Sketching software.

- **Mobility**: Eiliat and Pusca (2013) state in a research of digital sketching that "tablets are effective devices because of their mobility and convenience". "**Portable Devices**" for Digital Sketching enable designers to access their design wherever they are. The internet embedded in digital media facilitates digital sketches to join the "**Global Scale Communication and Collaboration**".

- **Immediacy**: With the development of technology, the Flexibility of Digital Sketching has been improved over the last decade; e.g., the more "**Intuitive Hand-Eye Coordination**" is allowed in Digital Sketching, and "**Immediate Visual Feedback**" is also provided to users. Previously, the lack of immediate feedback was considered as a drawback to using Digital Sketching until the digital tablet with a built-in screen became available. In addition, Brade et al. (2013) mention that features of "handwriting and gesture recognition" in some digital sketching tools may help to construct an effective representation of mental models.

- **Flexibility**: Some designers describe sketching as having higher Flexibility compared with "the rigidity of CAD software" (Rahman, 2016). But some researchers note that paper-based sketching probably doesn't have the higher level of capability to make immediate alterations (Marx, 2000; Dorta et al., 2008). However, Digital Sketching has the capability to "**Simplify and Speed up Modification**" with its "**Multiple Built-in Tools**" and "**Low Sunk Cost**". Since the operation is still relatively intuitive compared to CAD Modelling, the Flexibility of Digital Sketching is rated high.

- **Aesthetic Detail**: As a subcategory of Sketching, Digital Sketching can be used to create minimal details in a representation. Also, the inherited attributes of "**Improved Resolution and Complexity**" can enable digital sketches to achieve higher level of details than Traditional Sketching.

- **Engineering Detail**: According to the literature, the level of details regarding manufacturing and production information is still currently lower than CAD. However, new techniques, increased compatibility of the software to 3D Modelling tools, and the potential of the digital media may significantly improve the ability of Digital Sketching for dimensional and other engineering details.

- **Level of Aesthetics**: According to Larsson (2016), the reason he prefers to use traditional sketching as an ideation tool is that the outcome of traditional sketching is usually messy while the outcome of digital sketching is much cleaner and tidier. However, without the pre-mindset of keeping digitised files more formal, the outcomes of Digital Sketching during idea exploration can also be messy and untidy. At the same time, the "**Persuasive and High Aesthetic Attractiveness**" of digital sketches have been widely agreed (Chapter 1).

- **Amount of Representations**: The display of digital sketches relies on either a digital screen or printing. As shown in Figure 2.4(b), if not printing the sketches out, the Amount of Representations of Digital Sketching can be viewed at one time can be limited by the number of accessible screens. Similarly, in Figure 2.4(a), one benefit of using Traditional Sketching is free access to all the previous representations simultaneously. Arguably, using multiple windows or monitors to display digital sketches can be done in Digital Sketching but may not be practical at this stage for many design scenarios in practice.

(a) ***(b)***

Fig. 2.4 Amount of Representations: Traditional Sketching (a) vs Digital Sketching (b)

- **Holistic View of Objects**: This characteristic of Digital Sketching is limited by the "**Risk of Limited View Size**". The screen size of digital tablets can be an effective factor as well as the fixed 2D representation. However, the developing virtual reality environment for 3D Digital Sketching is promising for improving this capability.

- **Compatibility**: The transition from 2D to 3D is a huge transition in three-dimensional design disciplines. Digital Sketching offers an "**Easy 2D to 3D**" path and vice

versa with its "**Improved Resolution and Complexity**", "**Multiple Built-in Tools**", and "**Better Understanding of Forms**". Also, the transition gap between Traditional Sketching (2D traditional media) and CAD (3D digital media) can be narrowed by using Digital Sketching (2D and 3D digital media).

- **Use Cost**: Many studies suggest that using Digital Sketching can attain "**High Accuracy with Low Cost of Time and Efforts**", but the Use Cost of Digital Sketching is still considered higher than Traditional Sketching when the quality of the representation is not stressed. For example, there is no start-up or recharging of batteries to use paper and pen. However, the benefits of adopting digital media with Sketching is that Digital Sketching could be a more balanced tool in terms of both thinking and representation. In other words, its Use Cost during a design project could be more equally distributed between developing the design concepts and visualising the design representations.

- **Learning Cost**: As discussed in Subsection 1.4.3, Digital Sketching may generate "**Considerable Low Learning Frustration**" compared to Traditional Sketching training. However, the Learning Cost of Digital Sketching might be higher than CAD since freehand control is still involved.

According to the literature reviewed, the theoretical capability and potential of Digital Sketching are revealed with respect to the DTCs framework. As a result, the overarching finding is that Digital Sketching has a range of characteristics that suggest it could be used in a manner beyond its present use.

2.5 Chapter Summary

As is shown in Figure 2.5, the aim of this chapter is to gain support through literature and reasoning to answer research question 1 and reach a general understanding of Digital Sketching in theory. Traditional Sketching and CAD are identified as the neighbouring tools of Digital Sketching for comparisons, which is reflected in the design of the experiment in this study. A more comprehensive Design Tool Characteristics (DTCs) framework is created for breaking down the personality of design tools and mapping their affordances into measurable factors.

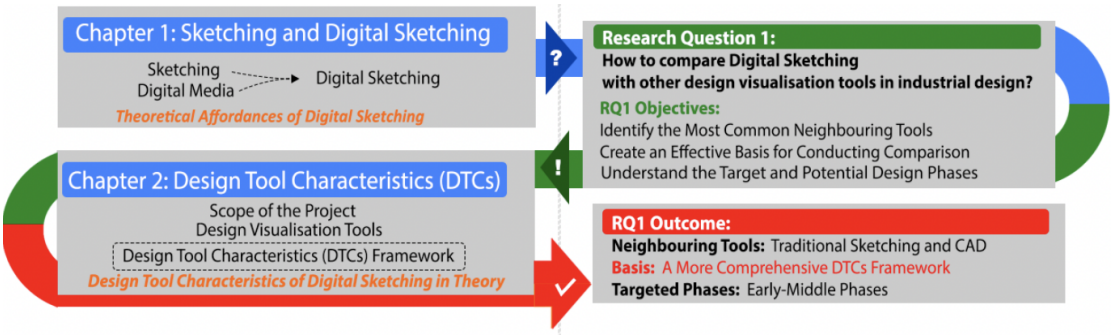


Fig. 2.5 Summary of Chapters One and Two

The DTCs of Digital Sketching are rated according to the narrative description of their affordances in Chapter 1 and other support identified from the literature.

As the theoretical potential of Digital Sketching is addressed, the potential use of Digital Sketching can be predicted by matching the expectations from the design process with the theoretical DTCs of Digital Sketching stated here. Therefore, a review of the industrial design process is conducted in the following chapter for a better understanding of the expectations and requirements of the potential design phases for targeting the use of Digital Sketching.

CHAPTER 3

INDUSTRIAL DESIGN PROCESS: CONTEXTUALISING THE USE OF DIGITAL SKETCHING

As described in Chapters 1 and 2, the use of digital media changes the design from many aspects, including the design process (Aldoy and Evans, 2011). This chapter provides an overview of the general design process and some specific industrial design processes, which aim to clarify the expectations of different design phases. Since the expectations and requirements of the design phases are described in greater detail, then when to utilise Digital Sketching for effective outcomes can be contextualised and discussed. The expectations on the design representations and the designers during the design process are interpreted with the Design Tool Characteristics (hereafter DTCs) framework. It further reflects the expectations of the design visualisation tools during the process. Eventually, DTCs that could be favoured based on the expectations in each design phase are highlighted to assist design tool selection. Understanding the expectations during the design process helps to exploit the design tools for more efficient design processes and effective design outcomes.

3.1 The Design Process

The design process is a highly complex mental process (Lawson, 2006:49); Roozenburg and Eekels (1995:83) state that there is still little agreement on it. There are many facts that could contribute to the complexity of understanding the design process, such as the ongoing development of technology, the diversity of process models and design projects, preferences of designers, etc. In other words, it is still difficult for the design process to be defined and perceived in one universal way. Hence, this uncertainty could lead to a vague or insufficient understanding of the design process by designers, especially novice designers and design students. It might generate long-lasting influence on

their tool-use behaviours.

In this section, the types of design process models and some typical models are reviewed to give a general understanding of the design process structure. The various types of design process models also suggest different perspectives for interpretation. It helps to select appropriate perspectives to describe the industrial design process to be used as a context in this study.

To be specific, two perspectives are identified and chosen from the literature to be the references for reviewing the design process. Partially because the two perspectives, the design activity and the design outcome, can be aligned with the criteria to analyse the Design Tool Characteristics (DTCs) of visualisation tools. These two perspectives help to break down the design process; hence, it can be associated with the Capability-related Characteristics of Design Tools (CCs) and the User-related Characteristics of Design Tools (UCs) of design tools.

In addition, the common attributes of the design process reflect the same aspects of the industrial design process that guide its detailed review in the next section.

3.1.1 Two Types of Design Process Model

Roozenburg and Eekels (1995:83-84) address three types of design process model in industrial product design, and each type has been agreed and evidenced by model examples. The three types are termed as the problem-solving process, phase models and the product development process. However, as the emphasis on marketing and manufacturing of the product development process models is not the core focus of this study, this type of design process model is not specifically addressed in this study. Therefore, two simplified categories of design process model are proposed here to provide context for analysing DTCs, which are the *activity-oriented design process* and the *outcome-oriented design process*.

- **The Activity-oriented Process: the User and the "Thinking" Perspective**
  The *activity-oriented design process* models represent the design process by describing designers' distinguishable "participatory design activities" (Hanington and Martin, 2012) when solving the design problem. In this type of design process model, designing is regarded as a problem-solving process (Roozenburg and Eekels, 1995; Ullman, 2009) or a solution-finding process (Pahl and Beitz, 2013) with steps. For some time, researchers have agreed that the purpose of conducting design activities is solving problems with innovative solutions. The logically op-

timised steps form a path with stops, which indicates the journey of a designer's behaviours (Aspelund, 2014). For example, Aspelund (2014) proposes a seven-stage design process, as shown in Figure 3.1, which simplifies the complexity of the design process so that design students could gain some guidance. Similarly, Ullman (2009:56-62) describes this type of design process as the mental process of a designer that occurs during design. According to Ullman (2009:56), this problem-solving process has four core activities; namely, "Understanding the Problem", "Generating Solutions", "Evaluating Solutions" and "Deciding". Briefly, this type of design process is a practical and fundamental way to understand and map the participatory design activities from the perspective of designers.

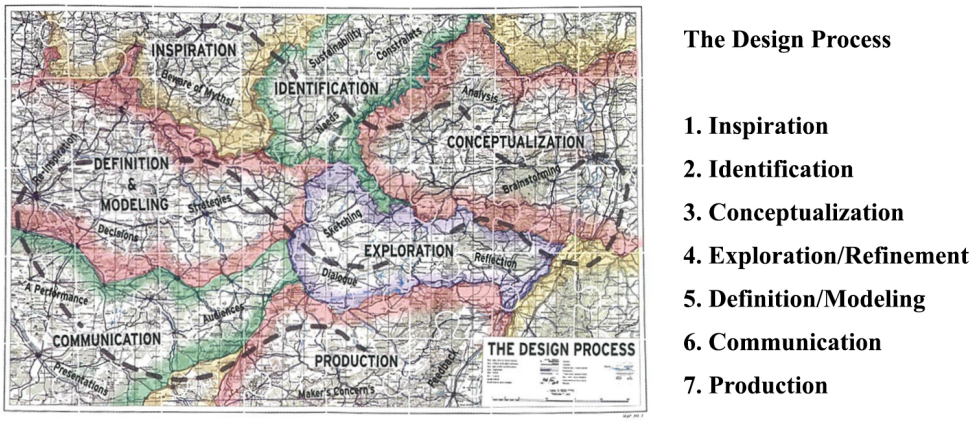


Fig. 3.1 The Seven Stages of the Design Process (Aspelund, 2014)

Besides, the problem-solving design process is not a fixed recipe but a spiral-like and iterative guide (Roozenburg and Eekels, 1995:92). The seeking of solutions for sometimes ill-defined design problems is a complex mental activity; Roozenburg and Eekels (1995:84) state that "the problem solving is the process of thought", which includes conscious and subconscious mental efforts to reach a solution(s). Even though there are optimised steps in the process, there is still a certain amount of freedom to conduct interactions among different steps.

Similarly, according to Lawson (2006:49), the design process is "seen as a negotiation between problem and solution through the three activities of analysis, synthesis and evaluation". The three simplified component activities also reveal the iterative nature of the design process. Basically, there are no strict boundaries between design phases/stages, nor restrictions on designers' natural behaviours. Instead, the design process recommends a systematic way of designing, and the transition between each phase in this type of design process model still includes uncertainty and offers designers the freedom to make their own decisions.

Therefore, the models of the *activity-oriented design process* are guidelines and references, while the specific design path chosen for any project by any designer can be customised to a certain extent. Furthermore, the tolerance of the design process on the diversity of design paths also applies to the diversity of the design outcomes.

- **The Outcome-oriented Process: the Tools/Representation Perspective** Different from the perspective of the design process models mentioned above, the outcome-oriented type of design process refers to the phase models that are defined by the distinguishable changes of design outcomes. In this design process model, the phases are determined by evaluating the levels of functional abstraction that correspond to the design representations (Roozenburg and Eekels, 1995). As illustrated in Figure 3.2, the method of dividing outcome-oriented phases can be described as grouping the design outcomes that share certain attributes within a period of the design process.

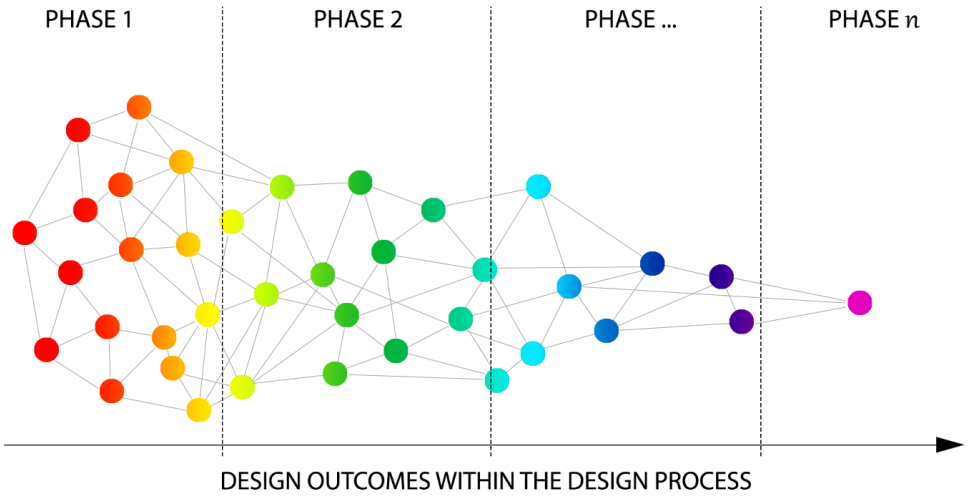


Fig. 3.2 The Dividing of Outcome-oriented Design Phases

According to Roozenburg and Eekels (1995), one of the most widely adopted phase models in Engineering and Product Design fields is based on the The Association of German Engineers (VDI) standard 2222. As is shown in Figure 3.3, this design process model contains four main phases: "Planning", "Conceptual Design", "Embodiment Design" and "Detailed Design". The Four Phases Model is adopted in Pahl and Beitz (2013:129-131)'s design process model, while the "Planning" phase (Ullman, 2009) is finely described as the "Planning and Task Clarification" phase. In terms of mechanical engineering design, Pahl and Beitz (2013:129-133) describe the changing path of the design outcomes during the design process as the specification of information, the optimisation of

principle/concept, the optimisation of layout and the optimisation of production. Hence, the requirement of each phase regarding design outcomes is also clear to see.

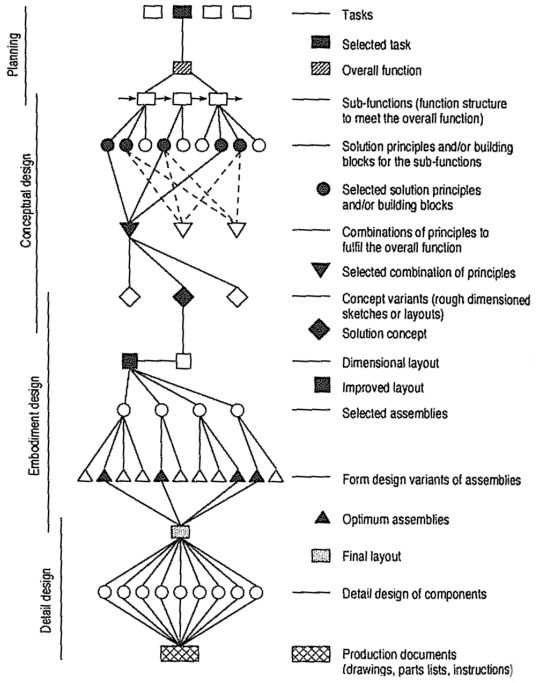


Fig. 3.3 A Four Phases Design Process Model (Roozenburg and Eekels, 1995)

Similarly, in terms of industrial design, Ulrich and Eppinger (2012:223) propose that the design process starts from the "Concept Development" phase, then to the "System Level Design", and finally to the "Detail Design, Testing and Refinement" phase. Meanwhile, the "Planning" phase is regarded as the beginning of the product development process (Figure 3.4) rather than the industrial design process, regardless if the product development process structural type is "Generic", "Spiral" or "Complex" (Ulrich and Eppinger, 2012). In other words, even though the Planning phase plays an important role in the design process, it can be categorised into the bigger picture; namely, the project/product development processes. Under this condition, the "Conceptual Design" phase (Pahl and Beitz, 2013; Ullman, 2009) or the "Concept Development" phase (Ulrich and Eppinger, 2012) can be seen as the beginning of the design process.

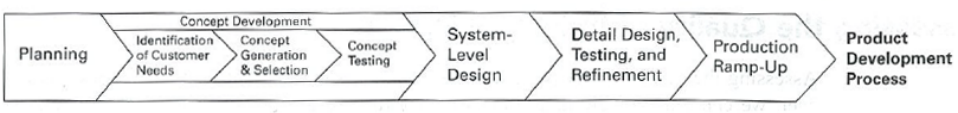


Fig. 3.4 The Product Development Process, Ulrich and Eppinger (2012)

Briefly, instead of setting constraints, this type of model reminds design practitioners of the more "practical" aspects of design, especially the development of design outcomes. The *outcome-oriented design process* helps design practitioners manage their projects by setting reasonable expectations regarding the development of design representations, and it also shows a recommended sequence of approaching good design outcomes.

In summary, the types of design process indicate two perspectives to better understand the design process. The expected design activities of designers during the design process are described, as well as the expected design outcomes generated with design tools.

3.1.2 The Common Attributes of the Design Process

From the design process models reviewed, some common attributes of the design process are revealed, which can also help to understand the industrial design process from the general design field. The identified common attributes are:

- **The Process: The Perspective of Process Models**
  The two types of design process model mentioned in Subsection 3.1.1 reveal two main perspectives of building and analysing design processes. Specifically, the Activity-oriented design process models represent the designer's workflow (Pahl and Beitz, 2013:128) while the Outcome-oriented design process models represent the idealised development of design outcomes.

  Analogous to the two perspectives of User-related Characteristics of Design Tools (UCs) and Capability-related Characteristics of Design Tools (CCs), it is clear that the study of design generally needs analysis from at least two perspectives. One is the subjective perspective, which is relevant to designer-related concepts; i.e., thinking, UCs, and the Activity-oriented design process. The other is the objective perspective, which is related to more practical and materialised aspects of design; i.e., representation, CCs, and the Outcome-oriented design process.

- **The Process: Emergence from Transitions**
  The design process – the development from a usually ill-defined problem to a specific solution – is complex. However, design process models indicate a general pattern to us by using abstractions. Regardless the type of design process model, the design process can be abstracted into components: designer's activities or stage outcomes.

- **The Process: Iterative Problem-solving and Problem-seeking**
  As the models in Subsection 3.1.1 show, the design process is iterative and endless (Lawson, 2006; Roozenburg and Eekels, 1995). It is also a mix of problem-seeking and problem-solving processes. In other words, designers discover new design problems by reflecting on solutions created during the design process. Since the process is one of thought that involves mental dialogues and decision-making procedures, it cannot be a simple linear flow. This attribute of the design process might accentuate the difficulty of understanding the design process, but it also contributes to its flexibility.

- **The Process: Flexible and Adaptive**
  As Lawson (2006:123) states, there is no infallibly correct process, design process models are not strict instructions. The design process offers freedom for every design project to suit itself in a working context. The logical sequence of the design process is recommended as a guideline which still has space to be modified and optimised by designers.

- **The Process: Embraces Uncertainty and Requires Decision Making**
  "Uncertainty" here refers to the uncertain boundaries between the "components" (Lawson, 2006:49), "stages" (Aspelund, 2014:3), "phases" (Roozenburg and Eekels, 1995; Pahl and Beitz, 2013; Ullman, 2009) or "gates" of the design process. It means that the progress of the design process requires decision-making. According to Pahl and Beitz (2013:128), the decisions of making progress are mainly about evaluating the satisfaction and compatibility of the outcomes from the previous phase or phases.

  Therefore, a clear design process model should help designers to make decisions by giving more detailed phase objectives (which do not necessarily influence the designer's freedom).

Therefore, the general attributes of the design process indicate an approach to understanding the industrial design process. The two main perspectives of the design process models reveal two ways to interpret the industrial design process; namely, the activities of designers and the outcomes of the use of design tools. Similarly, there are transitions occurring during the problem-solving and problem-seeking processes in industrial design that require the assistance of design tools. Additionally, the industrial design process is iterative, adaptive and flexible, so a working process model is built in the following section.

3.2 The Industrial Design Process

Digital Sketching is used in industrial design education and practices through the industrial design process, and itself can be a very beneficial tool for the industrial design community. Studies into Digital Sketching, Traditional Sketching and CAD in three-dimensional design disciplines are mostly conducted in architectural design and engineering design research. Compared with those design fields, there are fewer studies on Digital Sketching in Industrial Design. In Table 3.1, 20 similar studies of fundamental design tools in three-dimensional design disciplines are listed. 3 out of the 20 studies (highlighted in dark yellow) are most relevant to Digital Sketching, and another 3 (highlighted in light yellow) are studies where Digital Sketching is included partially. As such, the lack of studies on Digital Sketching in industrial design is clear. Therefore, the industrial design process is chosen as the context for this research of Digital Sketching after a review of similar studies.

Articles	Design Tools	Design Discipline(s)
Knight et al. (2005)	CAD vs Traditional Sketching	Architectural
Ibrahim and Rahimian (2010)	Traditional Sketching vs CAD	Architectural
Shih et al. (2015)	Traditional Sketching vs CAD	Architectural
Bilda and Demirkan (2003)	Traditional Sketching vs CAD	Architectural
Meneely (2007)	Digital Sketching	Architectural
Cheng and McKelvey (2005)	Digital Sketching	Architectural
Prats et al. (2009*a*)	Traditional Sketching vs CAD	Architectural/Industrial
Verdu et al. (2013)	Traditional Sketching vs Digital tools	Architectural
Viswanathan and Linsey (2011)	Physical Modelling	Engineering
Yang (2009)	Traditional Sketching	Engineering
Robertson and Radcliffe (2009)	CAD	Engineering
Booth et al. (2016)	Traditional Sketching	Engineering
Eiliat and Pusca (2013)	Digital Sketching	Engineering
Evans and Aldoy (2016)	Digital Tools	Industrial
Self and Pei (2014)	Traditional Sketching	Industrial
Alcaide-Marzal et al. (2013)	Traditional Sketching vs DSculpting	Industrial
Van der Lugt (2005)	Traditional Sketching	Industrial
Lutters et al. (2014)	Design Tools	Industrial Design
Aldoy and Evans (2011)	Digital Tools	Industrial
Haggman et al. (2015)	Sketch; CAD; Prototyping	Industrial

Table 3.1 Table of Similar Studies in Three-dimensional Design Disciplines

3.2.1 Introduction to Industrial Design

According to the World Design Organization (WDO), "industrial Design is a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experiences" (WDO, 2015). Industrial designers offer this professional service with a wide range of concerns about humans, technology, environment, etc. The industrial design process is a problem-solving process that also re-frames real-world problems as opportunities, and offers optimised solutions for the problems (IDSA, 2017; NCSU, 2017; WDO, 2015).

As discussed in Chapter 1 and Chapter 2, Digital Sketching can be a powerful tool, and more theoretical support on applying Digital Sketching in industrial design could benefit the community. Therefore, this project selected the industrial design process to contextualise the analysis of Digital Sketching. In addition, an adapted working model of the industrial design process with a detailed description is proposed at the end of this section to contextualise this study.

3.2.2 The Industrial Design Process Model

Generally, the common attributes of the design process influence the industrial design process. In other words, the industrial design process also has the characteristics of "uncertain", "flexible", "iterative", etc. Therefore, some well-established industrial design process models are reviewed to gain a deeper understanding of the expected activities and outcomes in the industrial design process. These process models are categorised based on the two perspectives proposed in Subsection 3.1.1. Also, the phases happening during the industrial design process are determined and discussed, which contribute to the formation of a working process model. The description of this working process model indicates the expectations of designers and design tools from the industrial design process.

- **The Activities in the Industrial Design Process**
  The activities of designers and the steps of the activities that are expected to be conducted are well described in many industrial design process models to assist designers in scheduling their design activities. Key technologies determine product viability and commercial potential, complete the initial product specification, and plan the product development cycle.
  - At the beginning of an industrial design project, an initial study of the design problem is expected. In particular, the study could include the investigation

of customer needs (Ulrich and Eppinger, 2012), the discovery of the product (Ullman, 2009) and the task clarification (Pahl and Beitz, 2013). Planning for the overall design project should also be considered as one of the main activities (Ullman, 2009; Pahl and Beitz, 2013). Designers can have insights into the project after the study of users, technical feasibility, market potential and sustainability. Once the information is accumulated and synthesised, the designers are very likely reaching the realisation (Autodesk, 2016) of the design problem.

- After the main design problem is revealed, the next professional activity starts: Conceptual Design (Ullman, 2009; Pahl and Beitz, 2013; IDSA, 2017). According to Ulrich and Eppinger (2012), the preliminary development and refinement of the concepts are also involved in the conceptualisation. In short, exploring the potential solutions of the design problems is a designer's main task in this phase.
- A design process requires both divergent and convergent design activities. The selection of concepts and further refinements are expected after conceptualisation (Ulrich and Eppinger, 2012; IDSA, 2017). The development and detailing of selected concept(s) are the favourable activities in this phase. Compared to conceptualisation, designers need to conduct more depth-first designing instead of breadth-first designing.
- In order to turn the concept into the solution, "Embodiment Design" (Pahl and Beitz, 2013; IDSA, 2017; Roozenburg and Eekels, 1995) follows after the finalisation of the concept. During the embodiment design phase, designers develop the concept in accordance with more practical criteria to meet production requirements. As Pahl and Beitz (2013:227-228) state, considerations for technical and economic factors are important; i.e., safety issues, assembly requirements, recycling methods, etc.
- "Detail Design" is recommended as the final phase before production in many industrial design process models (IDSA, 2017; Pahl and Beitz, 2013; Roozenburg and Eekels, 1995). Testing of the solution and other preparations for production are conducted during this phase. Coordination with engineers, manufacturers and other stakeholders is one of the key tasks for designers (Ulrich and Eppinger, 2012). Moreover, offering product support (Ullman, 2009) – which includes but is not limited to document data sheets and user manuals – is considered to be within the reasonable scope of work.

From the review of process models, phase-based activities of designers during the industrial design process are revealed. This description of the activities helps to map the general expectations of Design Tool Characteristics (DTCs) within the

industrial design process, especially the expectations of User-related Characteristics of Design Tools (UCs).

- **The Deliverable in the Industrial Design Process**
  The deliverables of each phase in the industrial design process are divergent; i.e., the types of document, the number of files and the resolution of the representations. According to Evans (2017), there are 32 types of design outcome that can be created during the industrial design process. However, a description of five common deliverables for the industrial design phases is identified from the literature.

  – According to Roozenburg and Eekels (1995), the design specification can be created after the initial study of the design project. The specification should clarify the overall function of the design with the project plan, which can assist designers to follow the path and manage the progress.

  – The deliverable of the conceptualisation should be preliminary solutions, and the ideal deliverable of this phase is a representation of broad concepts (Roozenburg and Eekels, 1995). Breadth-first rough sketches (Roozenburg and Eekels, 1995) are usually chosen as the proper representation for this design phase. As shown in Figure 3.5, rough sketches emphasis quantity over quality, which are mainly used to represent the designer's mental ideas.

Fig. 3.5 Rough Sketches in the Conceptualisation Phase

  – The deliverable of the product design development (Ullman, 2009; IDSA, 2017) is expected as refined solution(s) designed at the system level (Ulrich and Eppinger, 2012). Compared to the deliverable of the conceptualisation phase, the design development representations contain more details and carry richer information to explain the design more clearly. The quality of the concepts and the representations are considered higher priority in this phase. For example, the preliminary solutions are synthesised into refined alternatives with higher resolution in Figure 3.6.

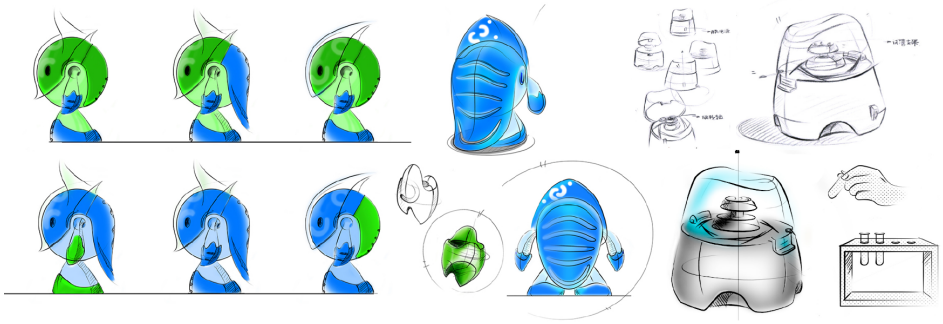


Fig. 3.6 Refined Solutions from Design Development

– Control drawings, models (Ulrich and Eppinger, 2012) and computer-aided renderings are expected as the fixed layouts (IDSA, 2017; Roozenburg and Eekels, 1995) in the embodiment phase. According to Pahl and Beitz (2013:228) and Roozenburg and Eekels (1995), size, definitive arrangement and materials are determined and delivered after the embodiment design phase. In other words, the deliverable of this phase is the optimum layout that fulfils specific requirements. However, the types of optimum layout can vary, as shown in Figure 3.7.

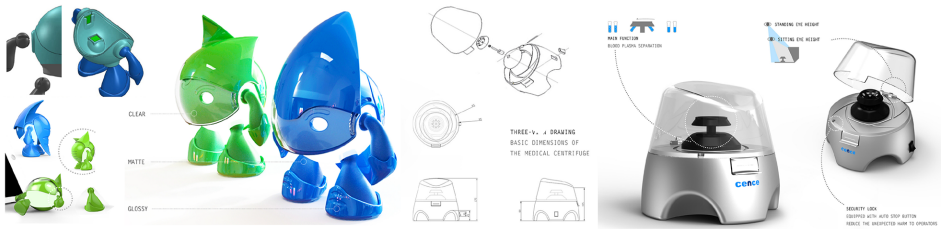


Fig. 3.7 Examples of Different Optimum Layouts

– The prototypes and documentation of the design solution are the deliverables of the detail design phase (IDSA, 2017; Roozenburg and Eekels, 1995). Product documents for finalising and supporting the design are created after different tests of the prototypes, which include but are not limited to the datasheet, supplier selection, recommended manufacturing processes, and user manuals (IDC, 2017). Creating and testing prototypes, especially the pre-production prototype, can prepare the design for manufacturing and production (Evans, 2017).

The expected deliverables of the industrial design process demonstrate certain requirements of the design tools, which can be mapped in terms of Design Tool Characteristics (DTCs) within the industrial design process.

In Table 3.2, the general expectations during the industrial design process are established. General expectations are broken down to the designer activities and design

deliverables. Expected activities coupled with the deliverables would not only help designers to have an intuitive understanding of the process but also clarify the requirements for the design visualisation tools.

Expectations in the Industrial Design Process		
General Steps	Activities	Deliverables
1	Planning and Clarification	Design Brief and Specification
2	Conceptualisation	Preliminary Solutions
3	Design Development	Refined Solution(s)
4	Design Embodiment	Optimum Layout
5	Pre-production Test and Support	Prototype and Documentation

Table 3.2 The Adapted Working Model of the Industrial Design Process

3.3 The Early and Middle Phases of the Industrial Design Process

3.3.1 Expectations of the Early and Middle Phases

The Early and Middle Phases here refer to the first four phases shown in Table 3.2. According to an analysis of literature shown in Table 3.3, similar studies of CAD and Sketching in three-dimensional design disciplines are conducted in the Early and Middle design phases. Firstly, the use of these design tools typically occurs in the Early-Middle design phases as highlighted in Table 3.3. Furthermore, one of the key concerns of applying digital tools is their impact on thinking, and thinking activities naturally decline over time during the design process. Therefore, the Early-Middle phases of the industrial design process are identified as the potential context to utilise Digital Sketching for a more efficient design process and more effective design outcomes in this study.

In order to map the expectations of Design Tool Characteristics (DTCs) in the Early-Middle industrial design phases, a detailed description of the Early-Middle phases is given based on the review of industrial design process models in Subsection 3.2.2. There are "significant" changes happening with both design activities and design deliverables/representations during the transitions from phase to phase. The specific exceptions from the Early-Middle industrial design phases are:

Articles	Design Tools	Discipline(s)	**Process Phase(s)**
Knight et al. (2005)	CAD vs Traditional Sketching	Architectural Design	Early
Ibrahim and Rahimian (2010)	Traditional Sketching vs CAD	Architectural Design	Early
Shih et al. (2015)	Traditional Sketching vs CAD	Architectural Design	Early
Bilda and Demirkan (2003)	Traditional Sketching vs CAD	Architectural Design	Early
Meneely (2007)	Digital Sketching	Architectural Design	Early
Cheng et al. (2005)	Digital Sketching	Architectural Design	Early
Prats et al. (2009*a*)	Traditional Sketching vs CAD	Architectural Design Industrial Design	Early
Verdu et al. (2013)	Traditional Sketching vs Digial tools	Architectural Design	Early-Middle
Viswanathan and Linsey (2011)	Physical Modelling	Engineering Design	Early
Yang (2009)	Traditional Sketching	Engineering Design	Early-Middle
Robertson and Radcliffe (2009)	CAD	Engineering Design	Early-Middle
Booth et al. (2016)	Traditional Sketching	Engineering Design	Early
Eiliat and Pusca (2013)	Digital Sketching	Engineering Design	Early-Middle
Evans and Aldoy (2016)	Digital Tools	Industrial Design	Overall
Self and Pei (2014)	Traditional Sketching	Industrial Design	Early
Alcaide-Marzal et al. (2013)	Traditional Sketching vs DSculpting	Industrial Design	Early
Van der Lugt (2005)	Traditional Sketching	Industrial Design	Early
Lutters et al. (2014)	Design Tools	Industrial Design	Overall
Aldoy and Evans (2011)	Digital Tools	Industrial Design	Overall
Haggman et al. (2015)	Sketch; CAD; Prototyping	Industrial Design	Early

Table 3.3 The Design Process Phases Studied in Similar Studies

The Early (1–2) Phase:

- **Designers:**
  According to the working process model, designers need to plan and clarify the design project then explore potential solutions through the conceptualisation process. Research and ideation skills are vital to the success of this phase. The design problem of a project should be clarified after the initial research. Hence, the next activity is finding the potential solutions to solve the problem.

  During conceptualisation, the number of concepts created is one of the most important criteria. In other words, thinking activity has higher priority than representation in this phase. Premature design fixation, committed to certain solutions too early, could lead the overall project to a poor design outcome. Briefly, designers should be more creative and keep exploring new alternatives in this phase regarding the design problem.

- **Deliverables:**
  A design brief should be created after the initial study, which specifies the design problem, customer needs and other concerns. The design brief can be documented in texts or visualised for communication.

  The representation type of the preliminary solutions generated from the conceptualisation phase can be various; namely, rough sketches (Roozenburg and Eekels,

1995) and concept models. The selection of representation type should consider the ease of the transition to the next deliverable. Also, preliminary solutions only need to be broad outlines of the overall function, interaction and appearance. Therefore, the detail of each concept is less important than the breadth of divergent thinking.

The Middle (3–4) Phase:

- **Designers:**
  During the middle design phase – namely, Design Development and Design Embodiment – designers should select concepts from the preliminary solutions and develop them into an optimum layout. Further external communications with others can happen during this phase. Hence, more ideas can help with the refinement and finalisation of selected concepts.

- **Deliverables:**
  The refined solutions are more vertical-developed solutions. Since the refinement needs advice from external sources, the representations created in this phase should explain the concepts more clearly and with greater resolution. The representation types of refined solutions can be communication sketches, CAD models and renderings. Similar to the preliminary solutions, the choice of the representation types and design tools should consider the transition from refined solutions to the optimum layout.

  The optimum layout is the final layout of the concept, which should accurately display the overall solution with all details. Considering the globalisation of design cooperation, the optimum layout should be easily delivered to all project participants and stakeholders. Since the optimum layout should be passed into production after testing and documentation, the requirements from production are critical criteria for choosing the optimum layout type.

The expectations of designers and deliverables in the Early-Middle industrial design phases are described based on the adapted working process model and relevant studies. Considering the expectations as criteria, the use of design visualisation tools during the process can be evaluated by examining how well this fulfils expectations.

3.3.2 Favourable Design Tool Characteristics in the Early-Middle Phases

In this subsection, the general expectations of the Early-Middle design phases are interpreted as specific expectations of DTCs. Therefore, the usability of a given design tool can be analysed within the process by using the DTCs framework. Eventually, it can help to evidence the potentials of using Digital Sketching in the Early-Middle Phases of the industrial design process.

According to the expectations in Subsection 3.3.1, the favourable DTCs in the Early and Middle Phases are suggested as follows in Table 3.4.

Design Process / DTCs	**Early Phase**		**Middle Phase**	
	Activities			
	Planning / Clarification	Conceptualisation	Design Development	Design Embodiment
	Deliverable			
	Brief / Specification	Preliminary Solutions	Refined Solution(s)	Optimum Layout
Ambiguity	High		Low	
Externalisation	High		High	
Internal Communication	High		Low-Medium	
External Communication	Low-Medium		High	
Problem Re-framing	High		Low	
Lateral Transformation	High		Low	
Vertical Transformation	Low-Medium		High	
Level of Commitment	Low		Medium-High	
Fidelity	Low-Medium		High	
Accuracy	Medium		High	
Mobility	Medium-High		High	
Immediacy	High		High	
Flexibility	High		Medium-High	
Aesthetic Detail	Low-Medium		High	
Engineering Detail	Low-Medium		High	
Level of Aesthetics	Medium		Medium-High	
Amount of Representations	High		Low	
Holistic View of Objects	Medium		High	
Compatibility	High		High	
Learning Cost	-		-	
Use Cost	Low		Low	
Emotional Commitment to Ideas	Low		Medium-High	
Expertise	-		-	
Expectation	Low-Medium		High	
User Accessibility	High		High	
User Loyalty	-		-	
User Share	-		-	

Table 3.4 Mapping the Expectations of DTCs in the Early-Middle Industrial Design Phases

3.4 Chapter Summary

The industrial design process, the context of this study, is reviewed in this chapter. Two perspectives to understand the industrial design process are identified from the review of literature on design process models: the designer's activities and the design deliverables.

An adapted working model of the industrial design process with expectations from these two perspectives is established. As suggested by relevant studies and empirical observations, the Early-Middle design phase is determined as the adjusted context of and scope for this study on the use of Digital Sketching. The final objective in research question 1 is met. The Early-Middle design phases in the industrial design process accommodate the types of design deliverable that Digital Sketching can potentially facilitate.

In order to understand the patterns of use and the applications of design visualisation tools in these phases, the narrative expectations on designers and design deliverables in the industrial design process are translated into the expectations on DTCs. Expected or favourable DTCs are used to discuss the potential use of Digital Sketching in theory in the following chapter – Chapter 4.

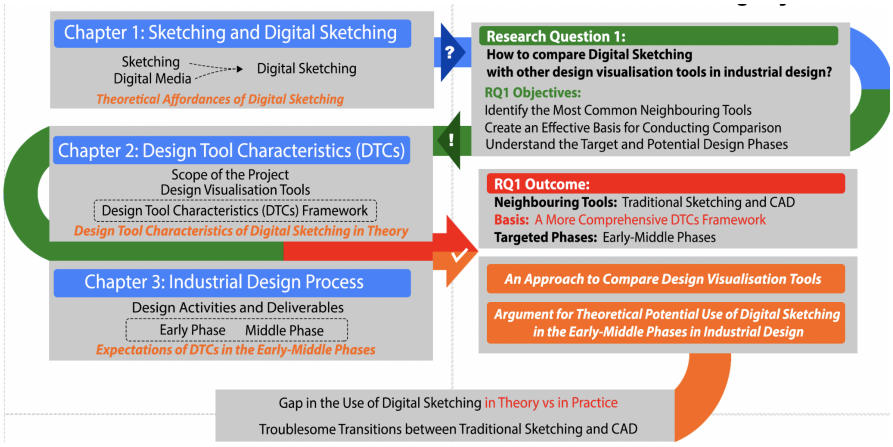


Fig. 3.8 The Summary Diagram of Chapters One, Two and Three

Figure 3.8 offers a figurative summary of the first three chapters that identifies a gap between the use of Digital Sketching during the Early-Middle industrial design phases in theory and in practice. A synthesised discussion of the literature review that created core research questions 2 and 3 of this study is given in Chapter 4. The research methodology and research design for answering the research questions are also provided.

CHAPTER 4

RESEARCH METHODOLOGY

In this chapter, a summary of the Review-based Descriptive Study is given to clarify the findings from the literature review on Digital Sketching. The theoretical affordances of Digital Sketching are described and discussed with the Design Tool Characteristics. The gap between the use of this tool in theory and in practice is noted, which leads to the core research questions of the study. To gain support for answering the research questions, a Comprehensive Prescriptive Study (Blessing and Chakrabarti, 2009) [18-19] is conducted and the methods used are presented. Specifically, semi-structured interviews and observations are chosen as the research methods. The design of the experiments and approaches for data collection for this study are proposed and discussed.

4.1 Discussion of the Review-based Descriptive Study 1

As mentioned in the Introduction, the type 3 Design Research Methodology (Blessing and Chakrabarti, 2009) [18-19] is used to guide this study. The project adopts the type 3 methodology for its four research stages: 1) research clarification; 2) review-based descriptive study I; 3) comprehensive prescriptive study; and 4) initial descriptive study II. The research progressions offered by this 4-stage methodology ensure the depth of the findings.

This methodology is chosen due to the nature of this study, which seeks support and evidence to evaluate Digital Sketching from both literature and experiment. In this section, the findings from the literature review at the stage of *review-based descriptive study I* are summarised and discussed. The *review-based descriptive study I* offers a preliminary answer to research question 1 and, in addition, the lack of support in the literature to reach the research goal that initialised core research questions 2 and 3. The design of the core research questions in this study aimed at providing more support for understanding the use of Digital Sketching.

4.1.1 How to Compare Digital Sketching With Other Design Visualisation Tools

Conducting comparisons between a design tool and its neighbouring tools in context – which can highlight the comparative strengths and barriers of using this tool – is an effective way to understand the tool and its use in the design process. During the review-based descriptive study I, research question 1 is proposed to find an effective basis to compare Digital Sketching with other design visualisation tools in industrial design. The Design Tool Characteristics (hereafter DTCs) framework is founded on the literature review, which provides a base to answer this question. In Figure 4.1, the objectives of the research question are listed and the outcomes from the review-based descriptive study I are given.

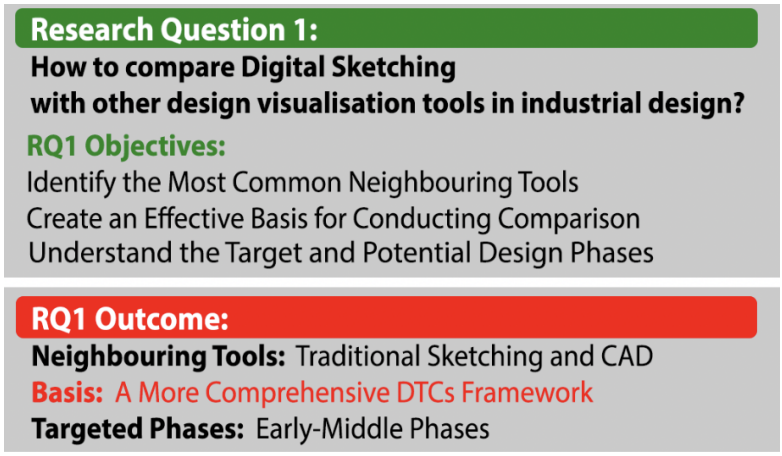


Fig. 4.1 Research Question 1: Objectives and Outcomes

To be specific, to understand the comparative uses of Digital Sketching in industrial design, the most common neighbouring tools with which to make a comparison are Traditional Sketching and CAD.

Relevant studies indicate that the use of tool characteristics could be an approach to understand, analyse and compare design tools. Hence, a more comprehensive DTCs framework is created, based on the literature, in Chapter 2 to guide an in-depth investigation into the use of Digital Sketching. The characteristics in the framework are either adopted from existing design tool evaluation frameworks (Self et al., 2009; Purcell and Gero, 1998) or individually identified from the literature in relevant fields (Goldschmidt, 1991; Tang et al., 2011; Self and Pei, 2014; Alcaide-Marzal et al., 2013; Evans and Aldoy, 2016; Strebel, 2017). The framework describes the nature of design tools from two perspectives; namely, the Capability-related Characteristics of Design Tools (CCs) and the User-related Characteristics of Design Tools (UCs). The theoretical affordances of Digital Sketching are provided from the results of using this framework. It will be fur-

ther used to guide the analysis of the experimental results in this study. The discussion and conclusion on the use of a DTCs framework for comparing design visualisation tools are given separately in Chapters 7 and 8.

Chapter 3 contextualises the study by introducing different design phases in the industrial design process where Digital Sketching and its neighbouring tools are used most frequently in practice. The general expectations for both the design deliverables and design tools during the design process are given. The Early-Middle phases of the industrial design process, the targeted phases in this study, are determined to be when and where Digital Sketching could be utilised for potentially more efficient and effective design.

4.1.2 Theoretical Use of Digital Sketching in the Early-Middle Phases

In Chapter 2, the theoretical characteristics of Digital Sketching is revealed by examining its theoretical affordances, identified in Chapter 1, with the DTCs framework. In Chapter 3, the expectations of the DTCs during the Early-Middle phases in the industrial design process are given, based on the literature.

By matching the DTCs of Digital Sketching and the expectations of the industrial design process, the potential use of Digital Sketching in the Early-Middle phases of the industrial design process is suggested. In Figure 4.2, the use of Digital Sketching based on its theoretical DTCs is figuratively illustrated for reference.

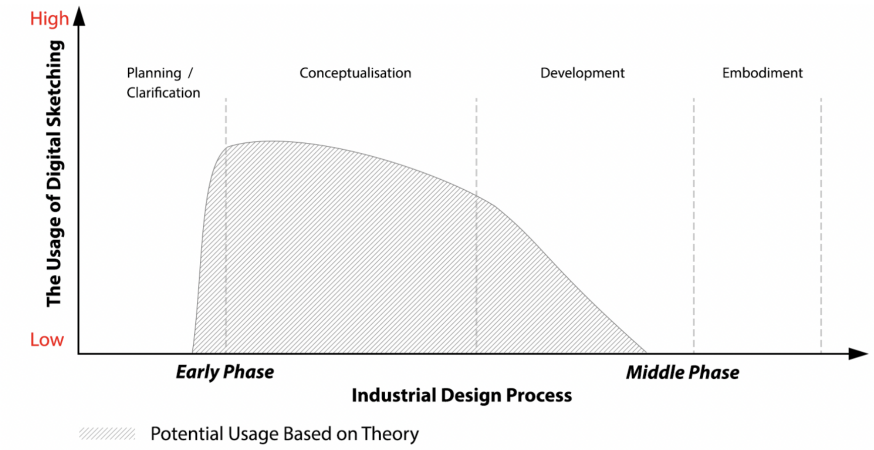


Fig. 4.2 Figurative Illustration of the Theoretical Use of Digital Sketching in the Early-Middle Industrial Design Process

To summarise, the theoretical DTCs of Digital Sketching appear to offer great support to the designers to meet various expectations of the industrial design process during

the Early-Middle phases. However, its current use in practice – based on the empirical observations of the author – seems not very popular in the industry (which is further discussed in the following subsection).

4.1.3 The Use of Digital Sketching in Theory Versus in Practice

In Chapter 1, the literature suggests that, theoretically, Digital Sketching can be a powerful tool in the design field along with some concerns. The potential use of Digital Sketching during the Early-Middle industrial design phases is also promising, which means Digital Sketching has the capability to perform effectively during the process.

However, based on literature and the author's empirical observations in education and industry, the use of Digital Sketching is relatively limited compared to more traditional visualisation tools in the early phases of the design process in industrial design practice, considering its theoretical potential in theory.

Figure 4.3 figuratively illustrates the theoretical potential and the current usage of Digital Sketching in the Early-Middle phases in industrial design practice. A gap between the use of Digital Sketching in theory and in practice is revealed, which suggests untapped design resources in the community. Hence, understanding and exploring the use of Digital Sketching in industrial design practice can be beneficial for developing more effective and efficient design processes and outcomes, and ultimately freeing up design resources. This leads to the formation of the core research question 2 of this study.

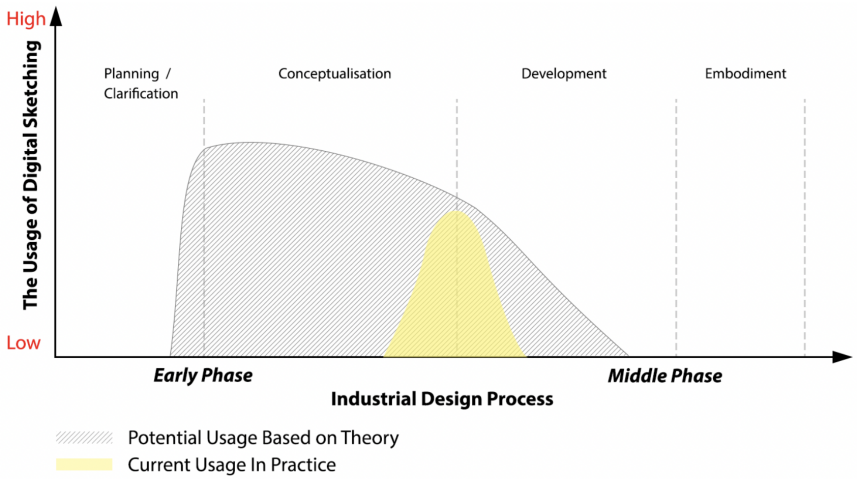


Fig. 4.3 The Use of Digital Sketching in the Industrial Design Process: Theory vs Practice

The research question 2, relevant objectives and research methods are proposed as follows.

Research Question 2: How does Digital Sketching manifest in industrial design practice during the Early-Middle design phases?

1. **Investigate the current use of Digital Sketching in industrial design practice**
   Interviews and observations are used to gather insights into the use of Digital Sketching and its neighbouring tools from design practitioners. Data is collected from both verbal and behavioural levels. The design and other details of the interviews and observation studies are documented in Sections 4.3 and 4.4.

2. **Explain the reasons behind the limited use of Digital Sketching in practice**
   With the DTCs framework, data collected from the investigation can be used to explain the causes of the current limited use of Digital Sketching in design practice. Key DTCs that influence the use of Digital Sketching in different design scenarios are identified after data coding and analysis, which can help to specify the causes of limited use and inspire new ways of more effective use.

3. **Reflect on the strengths and limitations of Digital Sketching in comparison with its neighbouring tools**
   Since the investigation, interviews and the observation studies also collected insights into the use of neighbouring tools – reflections on these uses can help either identify the inadequacies of Digital Sketching or offer new opportunities for using it.

To summarise, at the heart of this research question is understanding the patterns of use and applications of Digital Sketching in industrial design practice. Manifestation is defined by the dictionary (Manifestation, 2020) as "an event, action, or object that clearly shows or embodies something, especially a theory or an abstract idea". For this study, the definition of manifestation is the patterns of use and applications of Digital Sketching by practising industrial designers. In other words, the "embodiment" of the tool within the day-to-day activities of designers, which has been theorised in the *review-based descriptive study I*.

4.1.4 The Bipolarised Uses of Traditional Sketching and CAD

As mentioned in the introduction, there are troublesome transitions between the use of Traditional Sketching and CAD, the most common neighbouring tools of Digital Sketching in the industrial design process. These irksome transitions are a conundrum for many designers. This indicates the necessity and value in exploring the use of Digital Sketching since using Digital Sketching might be a way to address this problem.

In other words, Digital Sketching is a transitional tool that could potentially ease these transitions.

According to the literature and the empirical observations of the author, Traditional Sketching and CAD appear to have bi-polarised characteristics that could cause these transitions. At the same time, when to use them during the Early-Middle design phases – which differ from others since the expectations of each phase are different – needs to be considered. For example, the high Ambiguity of Traditional Sketching could contribute to the usage of this tool in the early industrial design phase, but the Ambiguity of CAD is low, which makes it a practical tool to meet manufacturing requirements. In Figure 4.4, the bi-polar usage of Traditional Sketching and CAD during the Early-Middle phases is figuratively illustrated to indicate the transitions that need to happen between these two tools.

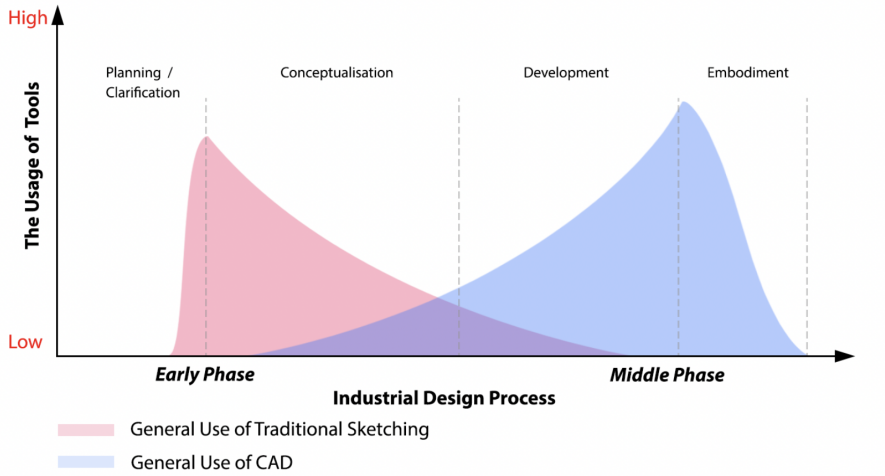


Fig. 4.4 The General Usage of Traditional Sketching and CAD in the Early-Middle Industrial Design Phases

Literature indicates Digital Sketching could be more moderate in many characteristics compared to the more bi-polarised Traditional Sketching and CAD. Mapping the potential usage of Digital Sketching with the other two tools in Figure 4.5 suggests that the transitions could be smoother and smaller if adopting Digital Sketching in the process. In other words, the use of Digital Sketching might help to generate a more desirable design experience and outcome during the transitions.

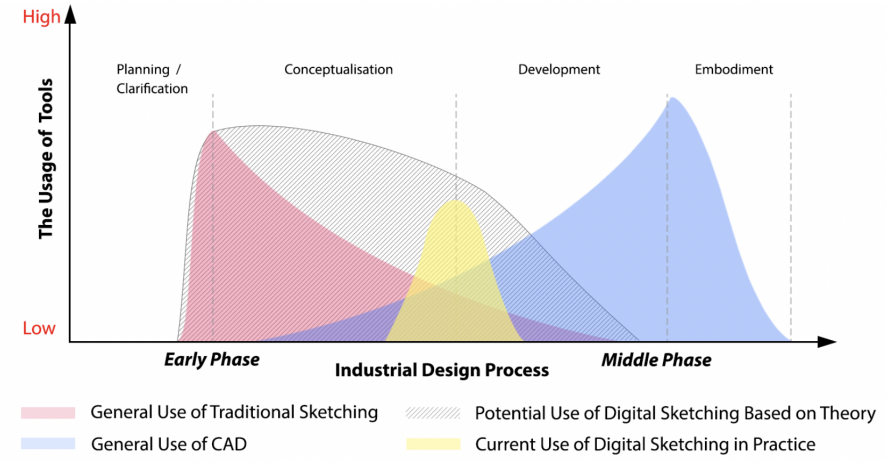


Fig. 4.5 The Use of Digital Sketching in Industrial Design

Therefore, research question 3 is designed to bring the transitional use of Digital Sketching into the investigation to define the barriers and opportunities surrounding the use of Digital Sketching to ease the troublesome transitions (between Traditional Sketching and CAD). Research question 3, objectives and research methods are as follows.

Research Question 3: Could Digital Sketching be a "pathway" to ease the troublesome transitions between Traditional Sketching and CAD?

1. **Explain the troublesome transitions between Traditional Sketching and CAD**
   A literature review was used to identify the troublesome transitions between Traditional Sketching and CAD in theory. Experimental data from the interviews and observation studies can be mapped with the DTCs framework to further explain why the transitions could be troublesome.

2. **Explain the limitations of using Digital Sketching in the early-middle design phases in industrial design practice**
   Reviewing the key DTCs that dictate the use, or the lack thereof, of Digital Sketching, the observation studies (see Chapter 6) are proposed to give a richer understanding of those limitations and barriers identified from the interview studies (see Chapter 5). Discussions and illustrations in Chapter 7 focus on some specific perceived barriers of using Digital Sketching with the knowledge of the theoretical potential and the investigation results from practice. This exploration and discussions are necessary for understanding Digital Sketching. When using CAD as an example, Use Cost is perceived as a barrier to using CAD in the early design phases, but many designers investigating the project developed a new way – "block CAD" – to lower this barrier in their practice. Therefore, this barrier to CAD is not necessarily a true barrier anymore in design practice. Hence, explor-

ing and discussing opportunities of using Digital Sketching in non-stereotypical ways can help to test and tackle down the barriers surrounding its employment.

3. **Explore the opportunity to solve some of the issues experienced with Traditional Sketching and CAD modelling using Digital Sketching**
   As issues experienced with Traditional Sketching and CAD Modelling are also revealed after the interview analysis in Chapter 5, especially the troublesome transitions between these two tools, then it is likewise an opportunity to try to solve them using Digital Sketching. If Digital Sketching can help with the issues, then the research findings can be used to free up design resources and improve the time efficiency of tool use in design practice. The observation study is used to test some specific DTCs for this purpose, which gives a richer understanding of the manifestation of these three tools and also reveals some opportunities and potentials for Digital Sketching to ease the troublesome transitions between Traditional Sketching and CAD. Further discussions and illustrations based on investigation results and practice in Chapter 7 are used to answer this research question.

Research question 3 aims at providing a comprehensive and up-to-date understanding of the use of Digital Sketching. It is designed to explore the comparative and transitional use of Digital Sketching in the Early-Middle phases of the industrial design process.

All in all, the relatively limited use of Digital Sketching in Industrial Design is revealed from the literature review. The DTCs of Digital Sketching also indicate that there are benefits for designers and design teams if adopting Digital Sketching during the design process. Overall, the study aspires to understand and explore the use of Digital Sketching during the Early-Middle design phases to achieve more effective design outcomes with a more efficient use of design tools.

Arguably, with a superior comprehensive understanding of the manifestation of Digital Sketching, as well as the barriers and opportunities surrounding its usage in industrial design practice, designers can explore and optimise its employment to create more effective design visualisations, gain more accurate feedback, and conduct more effective communications with good time efficiency and a user-friendly experience. The proposed research methods to answer the research questions are described and justified with more detail in the next section.

4.2 Justification of Selected Research Methods

A review of the 20 most relevant studies, as shown in Table 4.1, formed a base to identify effective methods for conducting the *comprehensive prescriptive study*. Designer interviews aimed to reveal their understanding, selection and use of design visualisation tools during the design process in practice. Unobtrusive observations is a promising approach to show how designers use the tools in practice, which could offer deeper insights into the barriers and opportunities of using the tools from a practical perspective. Interviews and non-interference observation were chosen as the research methods of this project to produce reliable data.

Interviews were employed to gather insights into the use of Digital Sketching in industrial design practice from design practitioners. To reach a more comprehensive and in-depth understanding of the use of Digital Sketching in practice, design practitioners were chosen to participate in the interviews. Key characteristics in the DTCs framework that dictate the usage, or lack thereof, of Digital Sketching in design practice were identified through interviews.

According to Martin and Hanington (2012), interviews are often coupled with observation as a research strategy to verify and humanise the data collected. Observations of designers in real-world design projects at their usual workplaces were conducted in this project to gather supplementary data on a behavioural level, which contribute to providing stronger support to the findings. The results of the interviews and observations help to answer research questions 2 and 3.

In addition, as highlighted in Table 4.1, a gap in the literature was identified. There are limited studies on design tools conducted with practising designers. In other words, design practitioners are less investigated in studies on design tool evaluations, and especially less observed in their natural industry settings. This phenomenon could be caused by various reasons, including but not limited to:

1). The accessibility of practising designers and,
2). The difficulties in structuring the observation in the industry setting.

Articles	Tools	Participants	Method
Knight et al. (2005)	CAD vs Traditional Sketching	Students	Observation
Ibrahim and Rahimian (2010)	Traditional Sketching vs CAD	Students	Observation
Shih et al. (2015)	Traditional Sketching vs CAD	Designers	Observation
Bilda et al. (2006)	Traditional Sketching vs CAD	Designers	Observation
Meneely (2007)	Digital Sketching	Students	Survey
Cheng and McKelvey (2005)	Digital Sketching	Students	Survey Observation
Prats et al. (2009*a*)	Traditional Sketching vs CAD	Designers	Observation
Verdu et al. (2013)	Traditional Sketching vs Digital Tools	Designers	Case Study
Viswanathan and Linsey (2011)	Physical Modelling	Students	Observation
Yang (2009)	Traditional Sketching	Students	Observation
Robertson and Radcliffe (2009)	CAD	Engineering Designers	Survey
Booth et al. (2016)	Traditional Sketching	Students	Survey Observation
Eiliat and Pusca (2013)	Digital Sketching	Students	Survey Observation
Evans and Aldoy (2016)	Digital Tools	Designers	Case Study
Self and Pei (2014)	Traditional Sketching	Students	Observation
Alcaide-Marzal et al. (2013)	Traditional Sketching vs DSculpting	Students	Observation
Van der Lugt (2005)	Traditional Sketching	Students	Observation
Lutters et al. (2014)	Design Tools	Designers	N/A
Aldoy and Evans (2011)	Digital Tools	Students Designers	Survey
Haggman et al. (2015)	Sketch; CAD; Prototyping	Designers	Survey Observation

Table 4.1 Research Methods Used in Similar Studies

However, observing practising designers select and use different design tools in different scenarios could 1) offer a richer understanding of the results/findings from the interview study, and 2) reveal opportunities for using Digital Sketching in practice on a behavioural level. Therefore, gathering deep insights from design practitioners is critical for this project to truly understand and explore the use of Digital Sketching in industrial design practice. The findings of this study would also narrow this gap in the literature and contribute to the domain knowledge.

Specifically, semi-structured interviews and observations were used in this study at the *comprehensive prescriptive study* stage. The ethics clearance regarding the research methods and data collection is given in Appendix C. A detailed design of the experiments is given in the following sections including the design of the interviews and observations as well as the methods for data collection and analysis.

4.3 Interview Study

Semi-structured interviews could potentially provide richer data than surveys. Conducting interviews is a traditional research method to gain the opinions, attitudes and perceptions of a certain group of people (Hanington and Martin, 2012). The semi-structured interviews with practising designers in this study are used to establish the experiences and understandings of designers with Traditional Sketching, Digital Sketching and CAD during the industrial design process. The interviews aim to gather insights from design practitioners regarding their uses of these design visualisation tools. It would help to reveal how the tools manifest in real-world industrial design practice to answer research question 2. The Design Tool Characteristics that are primarily dictating their uses can also be revealed. Hence, the interview questions are designed to elicit responses from designers that can be coded in terms of DTCs, and thus form a basis to answer the research questions.

4.3.1 Participant Interviews and Justification

As in Table 4.2, 11 participants with mixed levels of design experience were recruited from three design studios as well as one self-employed participant. Adding a diversity of participants' backgrounds helped the generalisation of the findings. At the same time, the participants' expertise levels, positions and roles in a design team within a working environment were documented in this study to determine and control those human factors which could have a significant influence on the User-related Characteristics of Design Tools (UCs) of Digital Sketching.

Participants were recruited through a professional social network – LinkedIn – by recruitment messages. A statement of consent and an interview consent form were given to and signed by participating volunteers. The interview with each participant took approximately 1–1.5 hours. Standardised open-ended interviews were conducted with the designers face-to-face in an individual manner, during May 2018 to July 2018, on campus at Swinburne University of Technology or in a private meeting room on the premises of the designer's office. Audio recordings, transcripts and pen-on-paper sketches were produced and collected from the interviews.

The interview participants were coded as P1–P12 for reference and discussion in the later chapters.

Participants	Experience (Years)	Company	Role
P1	>5	1	Project Leader
P2	≤ 5	1	Designer
P3	>5	2	Designer
P4	>5	3	Designer
P5	>5	1	Manager
P6	>5	2	Project Leader
P7	≤ 5	1	Designer
P8	>5	1	Designer
P9	≤ 5	1	Designer
P10	≤ 5	1	Designer
P11	>5	3	Manager
P12	>5	Self-employed	Designer

Table 4.2 Interview Participants

4.3.2 Interview Design and Process

Semi-structured interviews were used to gather the emotions, experiences and attitudes (Dorta et al., 2008; Self et al., 2009; Mustafa, 2013; Crilly, 2015) about the use of Digital Sketching and its neighbouring tools from the interview participants. Open questions focusing on design tool use and real-world design experience were asked during the interviews. The interview guide is provided in Appendix A. Audio recording, a transcript and sketches (if applicable) were collected from each interviewee. Notes were taken during the interview as supplementary material to record the information. The 25 interview questions are as follows.

Three questions regarding the general background of each participant were asked at the beginning of the interview to help clarify their level of expertise and their usual role in design practice. This information was collected because these factors may indicate certain associations between the selection and use of tools of the participant and the relevant User-related Characteristics of Design Tools (UCs); i.e., Expertise and User Loyalty.

General Information
How long have you been working as an Industrial/Product designer?
How long have you been in your current design team?
Can you briefly introduce your general design process?

Table 4.3 Questions of General Information in the Interview

Questions 1–4 are designed to focus on gaining insights into the Use Cost and Learning Cost of Digital Sketching as well as its neighbouring tools from a practising designer's perspective. The perceived Use Cost of Digital Sketching is an important part of describing how Digital Sketching manifests in design practice, which can help to answer research question 2. It could also indicate what motivates designers to select and use these tools during the design process. The Learning Cost could potentially shed light on how education experience affects the current usage of the tools in industry.

1. Which design tools do you use during the early design phase? Why? During the middle design phase? Why? During the late design phase? Why?
2. How long do you usually spend on using Traditional Sketching in a design project? What about Digital Sketching and CAD modelling?
3. Did you learn how to use Traditional Sketching, Digital Sketching, and CAD Modelling in your formal design education? If so, how long did you spend on learning and practising?
4. How is your experience of learning Traditional Sketching, Digital Sketching, and CAD?

5. Is it easy to make changes to ideas in Traditional Sketching? What about Digital Sketching and CAD Modelling?
6. Of Traditional Sketching, Digital Sketching, and CAD Modelling, which is more easy and effective for moving between design ideas (different solutions)?
7. Of Traditional Sketching, Digital Sketching, and CAD Modelling, which is more helpful for developing details and variations of one/the same design idea?
8. Are the design tools quick enough to catch up with your creative flow during the design process?

Follow-up Question: Do you think it is more related to the tool itself or your expertise/skills regarding this answer?

9. What tool and representation do you prefer to visualise your ideas in the early design phase? Why?
10. What tool and representation do you prefer to visualise your ideas in the middle design phase? Why?
11. What tool and representation do you prefer to visualise your ideas in the later design phase? Why?

Questions 5–11 were targeting to describe how designers use design tools to visualise, develop and modify design ideas in different design phases. The answers can be grouped and interpreted in term of DTCs to explain the use of Digital Sketching in practice and to reflect on the use of its neighbouring tools as well.

12. Which representation form is more appealing to you in the early/middle/later design phase? Why? (Level of Aesthetics)
13. Are traditional sketches enough to represent the engineering and artistic details of your mental images during the design process? What about digital sketches and CAD model renderings? (Engineering Detail and Artistic Detail)
14. Do traditional sketches offer you enough imagination space to reinterpret your design ideas? What about digital sketches and CAD model renderings?
Reverse: Do the representations display your ideas in a more constrained/unambiguous way? (Ambiguity)
15. Are traditional sketches accurate enough to match your mental images during the design process? What about digital sketches and CAD model renderings? (Fidelity)
16. Which tool will inspire/help you to rethink the design problem which means reconstructing your understanding of the design problems not the design solutions? (Problem Reframe)
17. When do you choose to change tools/media during the design process? and why do you think you switch to other tools? (Tendency to Switch Tools)
18. Do you feel you commit more to the idea after you change tools? (Level of Commitment)
19. During the switches of tools in the design process, what do you usually do and how is your experience? (Compatibility)
20. During the switches of tools, do you think the tool is easy for capturing all the design information from the previous design representations?
Follow-up Question: Do you also use other tools to assist your work when you do traditional sketches? What about when you do digital sketching and CAD Modelling? (Compatibility)
21. What kind of representation do you use to communicate your ideas with your teammates or other professional designers/engineers in different design phases? Why?
22. When do you communicate your ideas with your clients or other non-designer stakeholders? What kind of representation do you use, and why?
23. How many traditional sketches do you usually use to evaluate or work with your ideas at one time? What about digital sketches and CAD model renderings? (Amount of Representations)
24. Of sketches and the operation interfaces of CAD Modelling and Digital Sketching, which one offers you a better overview of your design? (Holistic View)
25. Which tool and its outcomes are more convenient to access and use? (Accessibility)

Questions 12–25 are designed more specifically for individual DTCs, as indicated above, which can help the interview participants think and reflect on their use of design tools and give deeper insights. Hence, the answers can be used to explain the causes of the current limited use of Digital Sketching.

The time span of each interview was 0.5–1.5 hours, which was considered sufficient for the designers to understand the topic, reflect on their daily use of the design tools and develop their answers to the questions. During the data analysis, the descriptions of

tool use were coded and generalised in terms of the Design Tool Characteristics (DTCs). The interview data collected were de-identified to ensure that the privacy, identity and related intellectual property were protected. In Chapter 5, the interview results are presented after transcription, coding and analysis.

4.3.3 Interview Data Processing and Coding Methods

The raw interview data were primarily collected in audio recording format, which was listened through by the author to grasp a general understanding of the data, then transcribed with Google Speech API to form the text files, then the transcriptions were corrected by the author again.

The collected interview data were coded using the inductive coding method (Miles et al., 1994). In other words, the transcriptions of the interview session were read and interpreted by the author/researcher (Thomas, 2006). The Design Tool Characteristics (DTCs) framework was used in data analysis as a guideline for mapping, interpreting and presenting the data. To be specific, a detailed protocol-based coding scheme is given in Chapter 5, Section 5.1, which is derived from credible relevant studies (Self, 2011; Tang, 2002; Knight et al., 2005) and adjusted for this particular study.

4.4 Observation Study

The aim of conducting observation in this project was to triangulate the interview results. Observation helps to avoid any bias that might occur in the interviews. At the same time, it can yield richer and deeper insights into how designers actually use Digital Sketching in practice. In other words, it enables reflections on the interview results by showing the usage and use-behaviours of design visualisation tools with designers in real-world practice.

The observation study can offer in-depth insights into the manifestation of Digital Sketching versus Traditional Sketching and CAD in practice with targeted resulting key Design Tool Characteristics (DTCs) from the interview study. It is a stepping stone to answering research question 3:

Could Digital Sketching be a “pathway” to ease transitions between Traditional Sketching and CAD during the Early-Middle design phases in industrial design?

4.4.1 Observation Participants and Justification

The observations of 4 industrial designers (8 sessions in total, 2 sessions per designer) were conducted during the Early-Middle phases of their design projects. The number of participants was decided based on similar studies in the relevant fields listed in Table 4.1 to ensure sufficient data could be obtained to get reliable results. Observations with design practitioners in similar studies are usually around 2–5 (Shih et al., 2015; Bilda et al., 2006). Besides, the observation study was mainly used to triangulate the interview results. The duration and environment of the observations were decided based on the nature of the study and references in similar studies.

In Table 4.6, observation participants' levels of experience and tools used in the observation sessions are given. The expertise of participants is distributed equally with senior designers (experience more than 5 years) and junior designers (experience less than 5 years) to control the variable. However, due to its nature, an unobtrusive observation method was adopted for a more accurate result of how designers use design tools in practice. The tools observed were selected by the participating designer, case by case, when the observation session was taken.

No.	Experience (Years)	S1 Tool(s)	S2 Tool(s)
Ob1	> 5	Traditional Sketching	Traditional Sketching
Ob2	> 5	Digital Sketching	Traditional and Digital Sketching
Ob3	≤ 5	Traditional Sketching	CAD and Traditional Sketching
Ob4	≤ 5	CAD and Traditional Sketching	CAD and Traditional Sketching

Table 4.6 Participants of the Observation Study

The observation participants were coded as Ob1–Ob4, and the observation sessions with each participant were coded as S1 for the first session and S2 for the second session.

4.4.2 Observation Design and Process

The observations took place at the design team's workplace. The size of the team was 20–50. As shown in Figure 4.6, the environment and setting of the observations were natural rather than contrived (Blessing and Chakrabarti, 2009) [85]. Designer behaviours using different tools were observed, video recorded, and then analysed during their daily design work with no influential interruption from the observers. Each observation session took approximately 30 minutes, including 25 minutes of tool-use behaviour filming and a 5-minute semi-structured follow-up interview. All the sessions were conducted in a 4-week period from July 2018 to August 2018.

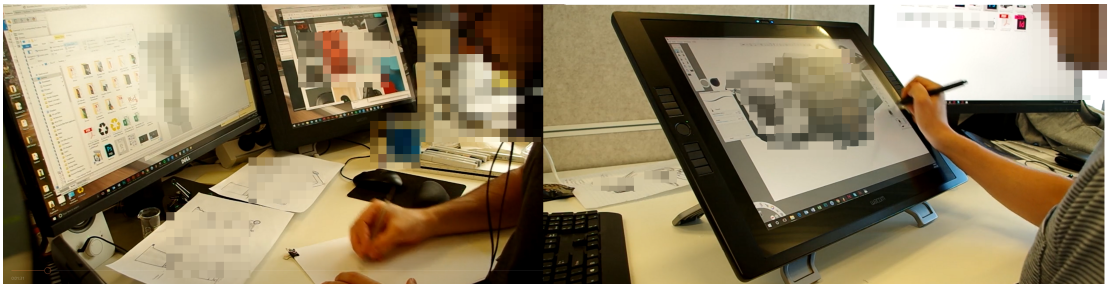


Fig. 4.6 Setting of the Observation Study

Appointments were made with the designers via emails before the start of each session to ensure observations fit the scope of the study. For example, participants explained the phase of the design process that the design project was in and the tools that would be used. Follow-up interviews were conducted to double-check this information to provide a more detailed context. Video recording was used for data collection during the observations. Note-taking was used in the follow-up interviews. The second observation session for each designer was either based on the first observation or spaced out over 2–3 weeks for the design projects to progress. The observation guidelines and the questions in the follow-up interviews are provided in Appendix B.

4.4.3 Observation Data Processing and Coding Methods

During data collection, both the design behaviours of the designers and the resulting design representations were gathered. The resulting design representations formed the major material to be analysed for the key Capability-related Characteristics of Design Tools (CCs). First, the types of these resulting design representations were clarified and coded with a well-accepted design representation taxonomy (Evans et al., 2010) from the Industrial Designers Society of America (IDSA). This was to avoid violating the intellectual properties of the real-world design projects and still be able to use the material for analysis. The videos and other supplementary information from the pre-check emails and follow-up interviews assisted this step of the coding. For example, the design phase – where a traditional sketch from the observation session is generated – helped to narrow down the options of design representation types in the first place. Hence the information on the sketch could be further analysed and matched against the descriptions on the taxonomy from IDSA.

An inductive coding method (Miles et al., 1994) was also used to guide the analysis of the observations. In terms of DTCs, the observations focused on a few resulting associations from the interviews, which were identified as essential to understanding the manifestation of Digital Sketching in practice. With the data and support from

the observations, the manifestation of Digital Sketching and its neighbouring tools in industrial design practice can be pictured in more depth.

The DTCs associations to be examined are described in Chapter 6 after the results of the interviews are given in Chapter 5. For each targeted DTCs association, specific coding criteria are given in Chapter 6 Section 6.1. The specific coding scheme is explained in more detail in Chapter 6 as well.

It is worth noting that the results from the observation study also form a basis to evaluate the Design Tool Characteristics (DTCs) framework as an approach for analysing design visualisation tools, and to triangulate the findings from the interview study.

4.5 Chapter Summary

In this chapter, the methods used in the study are described. The Design Research Methodology (DRM) is adopted for guiding an in-depth investigation. Type 3 research methodology from the DRM framework helped to plan and structure the study with objectives and research activities.

A summary of the *review-based descriptive study I* is given as well as a preliminary discussion of the answers to research question 1. The core research questions 2 and 3 are described and explained with relevant objectives to gain more support in understanding the use of Digital Sketching.

The research methods used in the *comprehensive study I* to answer core research questions 2 and 3 are semi-structured interviews and observations with design practitioners. On one hand, the methods are effective for collecting data to answer the research questions. On the other hand, a gap in the literature is further exposed in that there are very few studies on Digital Sketching in the industrial design field – especially studies conducted with design practitioners. Hence, an investigation with design practitioners is not only an effective way to explore the use of Digital Sketching in practice but it also contributes to domain knowledge.

To be specific, semi-structured interviews with design practitioners was determined as the major method to collect data on designers' perceptions of Digital Sketching and its neighbouring tools. The information of participants and the coding scheme is provided in this chapter. Data from the interviews were coded with the Design Tool Characteristics (DTCs) framework for analysis leading to the interview results. The observation study was planned to first triangulate the interview results and then enrich the find-

ings. The data collection and analysis is described here and explained in more detail in Chapter 6.

This chapter offers clarifications on research methodology, core research questions, objectives and research methods. By implementing the research methods, the results can then be employed to achieve the research objectives and answer the research questions. The interview results are given in Chapter 5, the observation results are presented in Chapter 6, and the discussions of the results are in Chapter 7.

CHAPTER 5

INTERVIEW RESULTS AND ANALYSIS

The semi-structured interviews with the practising designers are used to understand how Digital Sketching manifests in industrial design practice. The results of the interviews are given in this chapter; namely, the patterns of use and applications of Digital Sketching in practice. The interview results form a basis to further discuss how Digital Sketching manifests regarding effective visualisation and efficiency within the design process in Chapter 7. The reasons for its current limited and conservative use can also be explained by the interview results. The data regarding the use of its neighbouring tools is likewise used to reflect on the comparative strengths and barriers of Digital Sketching. Four tool-use conditions (*externalisation, internal communication, external communication* and *learning process*) are identified to help with the analysis of the interview data. The use of Digital Sketching under these tool-use conditions is examined separately, and the most frequently mentioned Design Tool Characteristics (DTCs) in each condition are highlighted as the key DTCs. Hence these DTCs are considered the key to understanding what dictates the use of Digital Sketching, with which the initial discussions on the comparative use of Digital Sketching are made. To summarise, with the interview results, a more comprehensive understanding of Digital Sketching can be developed for exploiting it to conduct more efficient design activities and reaching more effective design outcomes.

5.1 The Procedure for Analysing the Interview Data

As is shown in Figure 5.1, analysis of the interview data is conducted with an iterative coding and reviewing process. As a qualitative study, the interview content is firstly coded to index data when processing to facilitate retrieval and analysis (Blessing and Chakrabarti, 2009)[116]. As a result of this step, the overall coding is refined, and common examples of each of the Design Tool Characteristics (DTCs) from the interview data are given in Table 5.1 for quick retrieval and reference in the future. Also, intuitive

coding is conducted while processing the collected data.

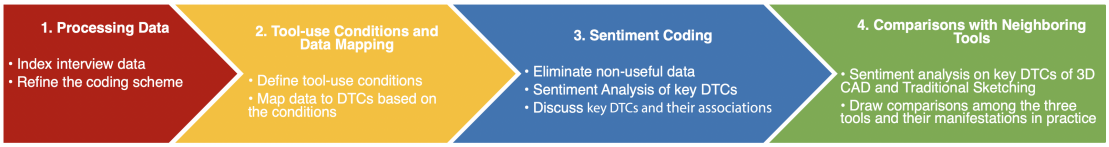


Fig. 5.1 Analysis Procedure of the Interviews

Stage 1. Processing Data

No.	Design Tool Characteristics	Examples in Interview Comments
1	Ambiguity	"loose/conceptual", "higher level of explanation of the concepts", "more space to develop the concept"
2	Lateral Transformation	"generate ideas", "as many ideas as possible", "ideation", "brainstorming"
3	Vertical Transformation	"add details", "change details", "develop variations", "make small adaptions"
4	Level of Commitment	"it's finished", "not locked into", "looks like a real product"
5	Level of Aesthetics	"neat/nicer/tidy/clean/cool/wow", "it looks better", "more realistic", "higher quality/resolution"
6	Accuracy	"accurate dimensions", "components will fit", "you have more control", "meet production"
7	Problem Reframing	"going back to the design brief", "doing research of the market/product"
8	Amount of Representations	"a few of X representations", "3 to 5 Y models", "hundreds of Z representations"
9	Immediacy	"lag/disconnect of X", "edit it more fluently", "there is no disconnection", "it feels just like X"
10	Flexibility	"easy/free/hard to change", "erase/duplicate", "chronological", "delete/undo/redo/copy/layers"
11	Mobility	"do it anytime", "in your bag", "carry it around", "mobile versions of X"
12	User Accessibility	"X is on my desk", "least/most accessible", "I haven't had a Y", "Z is cost prohibitive"
13.1	Level of Detail (Engineering)	"in scale", "size", "creating proportions", "critical mechanical details"
13.2	Level of Detail (Aesthetic)	"you can see what it looks like", "colour/shadow/lines details", "more resolved look", "A lot more content"
14	Holistic View of Objects	"I can view it in 3D", "we are able to see what it is"
15	Compatibility	"easy/difficult/need to change from X to Y", "Y can/can't capture the design from X"
16	Fidelity	"more refiner/resolved", "have clear image in my head", "have been done by X", "I understand/know what it is"
17	Learning Cost	"can't afford to learn a new tool", "took me years to learn"
18	Use Cost	"faster/easier", "time-consuming/too slow", "takes a couple of days/weeks/months to do X/Y/Z"
19	Tendency to Mix Tools	"I need to go/change between X and Y", "Keep X when do Z", "back and forth between X and Y"
20	Emotional Commitment to Ideas	"start picking all the faults", "loves the idea", "don't want to be stuck with the idea"
21	Expectation	"it should be more", "are going to have really great X representations", "expectations from clients"
22	Expertise	"depends on your skills/who is doing it", "one of the high skilled sketchers", "I am a bit rusty", "be able to produce"
23	User Loyalty	"I have never particularly enjoyed X", "I love/prefer Y", "I don't see the benefits of Z", "I am not a X/Y/Z user"
24	User Share	"it is/isn't industry standard", "Everyone or no one in my team uses X"

Table 5.1 Common Examples of the Design Tool Characteristics in Context

To be specific, discussions in Section 5.2 are supported by the evidence developed during the intuitive coding. For example, the general use of Digital Sketching in industrial design practice is noted as not popular compared to Traditional Sketching and 3D CAD. Another important finding from this stage is that the designer's attitude towards the tool can change based on the purposes of the design activities. This finding contributes to the formation of the tool-use conditions in the second analysis stage.

Stage 2. Tool-use Conditions and Data Mapping

After processing the raw interview data, the second step in the coding process is to define the different tool-use conditions in the industrial design process. Four main tool-use conditions are identified as a working category for further analysis of the interview data in this study. Specifically, participants would respond to the same question giving different opinions of the design visualisation tools based on the different conditions in which they would use them.

Due to the richness of the interview data, this working category helps to retrieve related data as per (Blessing and Chakrabarti, 2009)[117] and to control for variation in opinions based on the conditions in which the tools were used. However, further coding of Design Tool Characteristics is still based on the original context of the data to ensure the accuracy of the documentation and analysis. In other words, the interview data is grouped by the tool-use conditions but still in its original context for further mapping, which is enabled by the coding software product Nvivo 12.

Descriptions and examples of the tool-use conditions are given in Section 5.3. Mapping the interview data to individual DTCs is completed after the tool-use conditions are clarified. To summarise, the interview data is firstly labelled based on the tools mentioned, then grouped by the tool-use conditions and mapped to individual DTCs. A coding sample of the interview data across the three tools, four tool-use conditions, and all the DTCs is given in Appendix E for reference. This stage is to find the most frequently mentioned DTCs of Digital Sketching under each tool-use condition, which are defined as the key DTCs for discussions at the next sentiment coding stage (Figure 5.1). As an essential stage of the coding procedure, inter-rater reliability test is also conducted at this stage to ensure the reliability of the results. The sample data in Appendix E inclues 48 interview comments, greater than 10% of the overall interview data, which is used for the reliability measurement. This process is in line with recommendations set out in Saldaña (2015).

Stage 3. Sentiment Coding

Sentiment coding is the final coding step before analysis. The most frequently men-

tioned DTCs are coded by the positive or negative sentiments associated with characteristics within interview comments. This is used for understanding whether a particular manifestation of Digital Sketching in practice is considered positive or negative by the designers. Thus, what motivates and concerns designers to use Digital Sketching could be clarified with positive or negative sentiments. Table 5.2 shows examples of designers' different sentiments (positive/negative/mixed) regarding the key DTCs of Digital Sketching. Mixed sentiments are defined as showing both the positive and negative sides of the tool. Examples of the eliminated non-useful data are also given.

The result of the sentiment coding also offers a more contextualised and holistic understanding of the key DTCs. It opens up discussions on the associations between the key DTCs of Digital Sketching, which are identified based on how often the participants mention them as a group or within one comment. They could potentially support the development of a multifaceted understanding of the patterns of use of Digital Sketching.

Sentiments	**Definitions and Examples**
Positive	Clear indications of positive attitude towards the DTC, e.g. "I think hand sketching is the best [User Loyalty].", "It's easy and fast [Use Cost].", "I enjoy the freedom to change my ideas [Flexibility]."
Negative	Clear indications of negative attitude towards the DTC, e.g. "I can't see the benefit of using Digital Sketching [User Loyalty].", "It's time-consuming [Use Cost].", "It's not made for making big changes [Flexibility]."
Mixed	Clear descriptions of both positive and negative sides of the DTC, e.g. "It's more about the convenience of paper... but it may be a good improvement in more mobile versions of [Digital Sketching].", "Get something close to what you can do on the Wacom in a lot less time because you can undo on the Wacom, that takes practice as well.", "When you make a mistake, 'oh that's a bad line', then you rub it out and do it again. So, I think maybe the speed is a bit slower, but you get a better end result."
Non-useful	Unsure or unclear attitude towards the specific DTC, e.g. "I am not sure.", "It depends on the person/project.", "It's hard to say."

Table 5.2 Sentiment Analysis Guide and Examples

Stage 4. Comparisons With the Neighbouring Tools

Once what motivates and concerns the designers to use Digital Sketching is clear, then analysis on their opinions of the neighbouring tools – namely, Traditional Sketching and 3D CAD – is conducted. The comparisons are to complete a more comprehensive

understanding of the comparative use of Digital Sketching in design practice.

These comparisons are firstly drawn from the sentiment analysis results regarding these same key DTCs among the three tools. The key DTCs of Digital Sketching in each tool-use condition are used as the framework to compare how designers feel about these characteristics with the three different tools.

Based on the relevant references in the interview data, some other highly mentioned DTCs of the two neighbouring tools are noted. These DTCs of Traditional Sketching and CAD are defined as their own key DTCs, from which the different key DTCs among the three tools are also drawn for further analysis.

These two types of comparison are used to understand how Digital Sketching manifests in industrial design practice, and initially explores whether or not it could be a ”pathway” to ease the troublesome transitions between its neighbouring tools. The comparisons are discussed in Section 5.9.

To summarise, comparing Digital Sketching with its neighbouring tools enables us to expose the strengths (opportunities) and barriers of using Digital Sketching as well as the issues between Traditional Sketching and CAD.

5.2 Usage of Digital Sketching Among Participants

Table 5.3 below gives an overview of the use of Digital Sketching and its neighbouring tools by participants.

Participants	Experience (Years)	Company	Role	T.S.	D.S.	CAD
P1	>5	1	Project Leader	Yes	No	Yes
P2	≤ 5	1	Designer	Yes	No	Yes
P3	>5	2	Designer	Yes	Yes	Yes
P4	>5	3	Designer	Yes	Yes	Yes
P5	>5	1	Manager	Yes	Yes	Yes
P6	>5	2	Project Leader	Yes	Yes	Not anymore
P7	>5	1	Designer	Yes	Yes	Yes
P8	≤ 5	1	Designer	Yes	Yes	Yes
P9	≤ 5	1	Designer	Yes	Not anymore	Yes
P10	≤ 5	1	Designer	Yes	Not anymore	Yes
P11	>5	3	Manager	Yes	Not anymore	Yes
P12	>5	Self-employed	Designer	Yes	Not anymore	Yes

Table 5.3 The Usage of Design Tools by Interview Participants

Immediately, it is clear that the usage of Digital Sketching among the interview participants is lower than for both Traditional Sketching and CAD Modelling. To be specific,

only half of the participants (6/12) from all three different design firms used Digital Sketching in their design practice, which compares to the ratios of their use of Traditional Sketching (12/12) and CAD (11/12), which are significantly lower. This result concurs with one of the key premises of this study: the current use of Digital Sketching in practice is relatively limited.

The table indicates another interesting pattern among the participants in terms of their use of the three tools in that designer's persistence with Digital Sketching seems to be lower than with the neighbouring tools. One-third (4/12) of the interview participants had experience of using Digital Sketching at some point in their practice but have subsequently given up. This situation only happened to one specific interview participant (P6) for CAD, which is due to their current role in the creative team at the workplace. For Traditional Sketching, none of the participants had completely abandoned using Traditional Sketching since they learnt it.

5.3 Tool-use Conditions in Industrial Design Practice

Interview data is coded with the coding scheme shown in Figure 5.2.

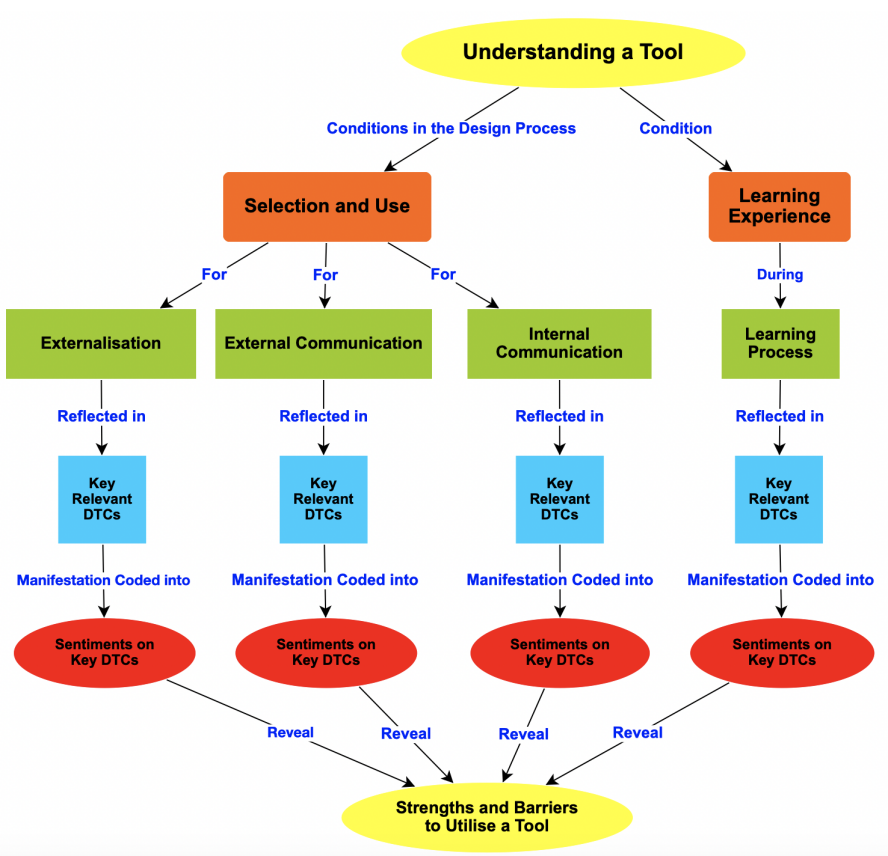


Fig. 5.2 Interview Coding Structure

Briefly, the interview content regarding each tool is first coded into different tool-use conditions, then coded to the relevant DTCs. As an example, a comment from P6 (see Table 5.3), "digital sketches have more 'wow' factor to the clients", is first grouped to the tool – Digital Sketching – under the *external communication* tool-use condition. Then, this comment is coded into the relevant DTC, which is the "Level of Aesthetics" (see No. 5 in Table 5.1) in this case.

After that, the most frequently mentioned DTCs in each tool-use condition are identified as the key DTCs, after which the associated sentiments (Positive, Negative or Mixed) are coded. Using the previous comment as an example, the "wow" is the basis to code a positive sentiment, which contributes to the discussion of the opportunity surrounding the use of Digital Sketching for offering a high Level of Aesthetics in practice.

Table 5.4 lists the four tool-use conditions identified to contextualise the use of tools for different purposes.

Condition	Definition	Examples
Externalisation	Using design tools for generating/visualising ideas	Statements or clear indications, e.g. "Get the idea out", "Change the details"
External Communication	Using design tools to visualise ideas for clients/other non-designer stakeholders	Statements or clear indications, e.g. "For clients", "Final presentation", "Pitch to clients"
Internal Communication	Using design tools to visualise ideas for in-team communications	Statements or clear indications, e.g. "Internal meeting/discussion", "show ideas to team member(s)"
Learning Process	Experiences of learning or using while learning the tools	Statements or clear indications, e.g. "When I learnt it at university", "I self-taught myself"

Table 5.4 Four General Tool-use Conditions in Industrial Design Process

Externalisation can be considered as activities externalising the mental images of the designers, generating creativity-led design visualisations, and reflecting upon them. It has been described in some studies as "Dialogue with Self" (Goldschmidt, 1991) or "I-representation" (Jonson, 2002).

Internal communication and *external communication* are adopted from the "Mode of Communication" (Self et al., 2009) based on literature reviews and the author's experiences observing practice. *Internal communication*, in this study, refers to the tool-use conditions when designers use design tools and the representations they create to communicate with their teammates; namely, other designers or engineers in the design project. *External communication* could be considered as the use of both design tools and representations to communicate design intentions to non-designers, mostly clients and other stakeholders. In this study, "clients" are used interchangeably with "clients

and other non-designer stakeholders" in *external communication* for a concise discussion. This is because participants were primarily referring to the clients in a tool-use condition but were also (occasionally) including other non-designer stakeholders. For example, for external communication, managers outside of the project team in a design department/company are considered as other non-designer stakeholders in this study.

External communication as a condition interacts with the design practice in many ways, not just the final presentation of design. For example, the scope and effectiveness of the *external communication*, as well as the collaboration before/in/after the communication activities, could affect not only the design process but also the use of design tools by changing designers' way of thinking.

Learning process is nominated as another condition in order to include the tool learning experience (as well as early use experience) into the analysis, which might have significant influences on the selection and use of certain tools later on in the designer's career. Following this coding scheme, the key DTCs and sentiments of Digital Sketching are analysed by the tool-use conditions *externalisation* in Section 5.4; *external communication* in Section 5.5; *internal communication* in Section 5.6; and the *learning process* in Section 5.7. Comparisons of these DTCs with the neighbouring tools are drawn in Section 5.9. Within each section, the most frequently mentioned DTCs and the associations between them are presented along with the sentiments.

5.4 Key DTCs of Digital Sketching for Externalisation

As mentioned above, *externalisation* is used to describe the tool-use condition where designers externalise thoughts through the use of design representation/tools, as well as reflect and iterate designs (Self and Pei, 2014; Bouchard et al., 2006). This tool-use condition happens primarily in the Early-Middle phase but also could happen in later phases during the design process. The 10 most frequently mentioned Design Tool Characteristics (DTCs) that dictate the patterns of use of Digital Sketching in *externalisation* are coded from the interview data as is in Figure 5.3.

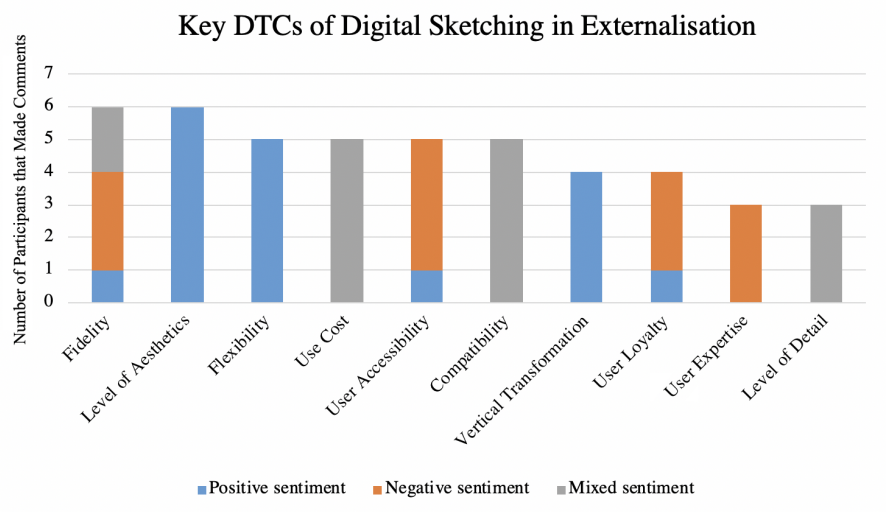


Fig. 5.3 Key DTCs of Using Digital Sketching for Externalisation

Fidelity, Level of Aesthetics, Flexibility, Use Cost, User Accessibility and **Compatibility** are mentioned most frequently by the participants with respect to *externalisation*. **Vertical Transformation, User Loyalty, User Expertise** and **Level of Detail** are also considered as key DTCs in this tool-use condition. The data on sentiments of these key DTCs suggest the designers share a complex attitude towards using Digital Sketching when they need to externalise their mental images to the physical world (get the ideas out of their heads).

To be specific, participants have some highly positive sentiments on Level of Aesthetics, Flexibility and Vertical Transformation using this tool for *externalisation*. At the same time, they also have concerns and considerations as is shown in their negative or mixed comments on the other key DTCs. From the data on sentiments of the key DTCs, designers have mixed or intricate feelings about applying this tool in *externalisation* during the Early-Middle phases in industrial design.

Additionally, based on the interview data, some of these DTCs are frequently mentioned together when answering one interview question, which suggests these DTCs may have a level of association with each other. These potential associations of certain DTCs could offer a more in-depth understanding of the current use of this tool. For example, positive sentiments towards one characteristic could be associated with negative sentiments of others.

To better understand the data, the interview comments in which these key DTCs were mentioned are reviewed to identify any groups or associations between DTCs that could enable multifaceted perspectives when interpreting the data.

5.4.1 Externalisation: Fidelity, Level of Aesthetics, Use Cost and Their Associations

According to the participants, current considerations regarding the use of Digital Sketching in *externalisation* during the Early-Middle design phases, compared with Traditional Sketching, include the requirements of a higher level of Fidelity for designers to start working with it and an associated higher Use Cost. Participants suggest that Digital Sketching requires a higher level of Fidelity to start/use than Traditional Sketching, which means they need a clearer mental image of the design before they jump into Digital Sketching.

For example, designers suggest that the design concept should "already be done on paper" (P3) or "by hand sketch" (P12) and, once they "have got a more fleshed out idea" (P12) and a "relatively well-developed concept" (P10), then they can move into Digital Sketching. This is consistent with literature that outlines the current limited use of Digital Sketching within the design practice as a beautifying tool for traditional sketches before CAD. Some of the potential reasons behind this finding are indicated in references to Use Cost, User Loyalty, Expertise and Flexibility associated with Level of Aesthetics. Figure 5.4 illustrates these associations between the key DTCs, which are further discussed below. Note that the size of the circles in the Figures 5.4–5.7 reflects the number of references of the characteristics made in the interview data.

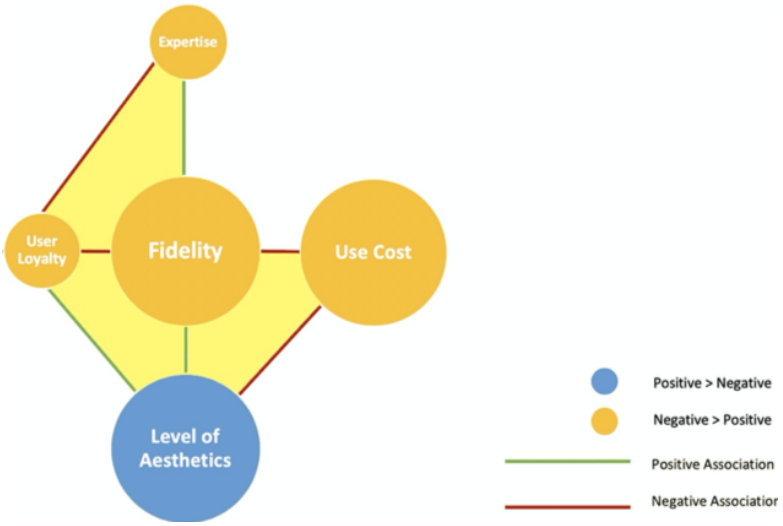


Fig. 5.4 Associations Between Fidelity, Level of Aesthetics and Use Cost in Externalisation

Participants show mixed sentiments towards the Use Cost of Digital Sketching in *externalisation* and positive sentiments towards its Level of Aesthetics. In other words, designers associate the use of Digital Sketching with a relatively high Use Cost but also

a high Level of Aesthetics. This association leads to a typical interpretation of Digital Sketching that it requires "a more fleshed out idea" (P12) to start with, so designers can avoid spending too much time on something less worthy. A total of 5 out of 6 participants mention Fidelity of Digital Sketching with negative or mixed sentiments. Hence, it seems that the requirement of Fidelity (the more fleshed-out idea) creates a threshold before which using Digital Sketching for *externalisation* is not necessarily preferable.

Besides, participants indicate that this impression with the Fidelity requirement of Digital Sketching may also relate to designers' low level of Expertise of Digital Sketching that can make it a time-consuming tool. Similarly, their negative sentiments on User Loyalty for this tool could make its employment for low Fidelity visualisations in the Early-Middle phases less popular, as they are unwilling to change their habits of using Traditional Sketching.

The different associations between these key DTCs are based on how often the participants mention them as a group or within one comment. Negative associations between Expertise, User Loyalty and Fidelity in *externalisation* are mentioned a few times by different participants in the interview data. For example, as participant 9 (P9) stated, "I don't tend to use my Wacom or anything like that [Digital Sketching] because I'm just being really used to using pen and paper to sketch [User Loyalty]." However, participants also recognise the benefits of the higher level of Fidelity once they pass this threshold, which is "increasing the clarity and being able to show more details" (P10) and "more refined ideas" (P12).

Participants show highly positive sentiments (6/6) towards the Level of Aesthetics of Digital Sketching in *externalisation*. They suggest the higher Level of Aesthetics offered by Digital Sketching can contribute to externalise higher Fidelity design representations that are actually worth the relatively higher Use Cost because they are beneficial for promoting the design progress and development. As an example, designers do not complain much about the Use Cost when considering the Level of Aesthetics, and they are satisfied with the "nicer", "cleaner" and "more realistic" visualisations that also give "atmosphere" to the design.

Therefore, the interview data suggests that designers associate using Digital Sketching with a requirement of a clearer mental image of the design; hence, more time could be spent on visualising this clearer image in Digital Sketching, which also discourages them from using the tool in the very early phases in design practice. However, as they spend more time on visualising the more developed design concepts, the design also evolves and progresses. Hence, participants suggest that most of the time they can justify the Use Cost for a more professional look, and they are happy to do so except in

the very early phases of the design process.

In other words, according to the interview participants, Fidelity, Level of Aesthetics and Use Cost of Digital Sketching in *externalisation* could form a relatively positive association of DTCs. The data also suggest that the Level of Aesthetics, and sometimes together with the Fidelity offered by Digital Sketching, can be desirable after the very early phases in the design process. The associations between these key DTCs indicate that a more balanced and strategic use of Digital Sketching could be expected and a better utilisation of the design resource.

5.4.2 Externalisation: Flexibility, Vertical Transformation, Use Cost, Level of Detail and Their Associations

As is shown in Figure 5.5, a positive association of Flexibility, Use Cost, Vertical Transformation and Level of Detail is noted from the interview data. The participants show highly positive sentiments (5/5) towards the Flexibility of Digital Sketching in *externalisation*. According to four participants, the high Flexibility of Digital Sketching in terms of duplicating and modifying design representations can significantly reduce the Use Cost for designers when conducting Vertical Transformations on their design ideas; consequently, this could potentially increase the Level of Detail of their design.

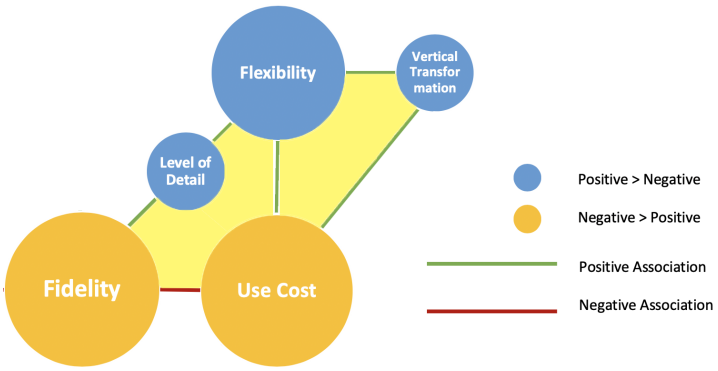


Fig. 5.5 Associations Between Flexibility, Vertical Transformation, Use Cost and Level of Detail in Externalisation

In other words, when using Digital Sketching, designers can easily duplicate the same design form and change a few details (buttons, fillets, handles, etc.), and/or apply different colour schemes, materials and textures on the duplicated design forms, hence turning them into new design variations. As the design activities related to Vertical Transformation are more likely to happen once the design reaches a certain level of Fidelity, this positive loop of these four DTCs occurs after the very early phases in the

design process.

According to the interview data, performing Vertical Transformation with Digital Sketching during the Early-Middle design stages is flexible and time-saving. As participant P11 stated: "You can have layers, you can go in and edit it and then if we actually decided that we want to change that design detail, 'can we try three different handles?', you can just do that digitally over the top, or save up copies, or even have different layers to turn on and off in Digital Sketching. So, it is much faster to do iterative work or refinement work [in Digital Sketching]." The interview participants suggest that Digital Sketching is very flexible for making quick changes and refining details in the Early-Middle design stages. Examples of techniques and features that are used for conducting Vertical Transformation in Digital Sketching are also mentioned in the interviews: "Produce variations based on duplicated silhouettes" (P3), and "copy colour palettes" (P7). Also, according to the participants, the compatibility with CAD and the online resources of Digital Sketching could contribute to the high level of Vertical Transformation in this tool. Designers can use "screenshot from block CAD" (P8) or "textures from online images" (P10) to add various Aesthetic Detail to the design concept and hence turn it into "different design variations" (P10).

To summarise, for *externalisation*, the interview data indicate that Digital Sketching has high Vertical Transformation ability by facilitating Aesthetic Detail development with good Flexibility and low Use Cost. Hence, more flexible and time-efficient uses of Digital Sketching for generating and externalising design variations could be an opportunity worth noting for utilising this tool in *externalisation*.

5.4.3 Externalisation: Expertise, User Loyalty, User Accessibility and Their Associations

As suggested by the interview data, designers value the freedom of choosing the time and locations to externalise their ideas, which brings about their considerations towards the User Accessibility of Digital Sketching devices. Here, participants show primarily negative sentiments (4 out of 5 participants) towards the User Accessibility of this tool in *externalisation*. Unlike in the automotive design field, the User Share of Digital Sketching tablets in industrial product design industry is relatively smaller than pen and paper for Traditional Sketching. At the same time, computers or laptops for CAD are considered a necessity for industrial design projects going into manufacturing. Hence, the low User Share of Digital Sketching devices in the industry also establishes the low User Accessibility of the tool for designers.

For instance, as participant P1 admitted: "In most of my roles, I haven't had one [Digital Sketching tablet] available to me and you really have to want to use it a lot to commit to buying one." Having devices for Digital Sketching at the workplace is not necessarily a standard in the industrial design industry at the moment, and it is cost-prohibitive for small design studios/firms. Even though the software price for Digital Sketching is lower than a CAD software licence, the use of CAD is the current standard and a necessity in industrial design practice.

In detail, the interview data indicate that the low User Accessibility also contributes to the fact that designers have less chance to practise their skills at their workplace and hence could easily have negative sentiments (3 out of 3 participants) towards their level of Expertise on this tool. In other words, these practising designers suggest that their current level of Expertise can be a barrier for them to use Digital Sketching in their daily work. The Learning Cost or the lack of Digital Sketching training during their formal education is also a contributing factor to this situation, which is further discussed in Section 5.7. Based on the interview data, lacking User Expertise can also cause high Use Cost as the designers cannot effectively manipulate the tool, which leads to low User Loyalty as inefficient users.

The associations between User Accessibility, User Loyalty and User Expertise are figuratively illustrated in Figure 5.6. Their negative associations could form a potential barrier that prohibits designers from learning and using this tool, especially for practising designers. For example, designers consider that "probably if I was good at Digital Sketching, I would have used it" (P9), or "I just haven't really developed that skill further, that's why if I have an idea, I will just try to sketch on paper" (P2).

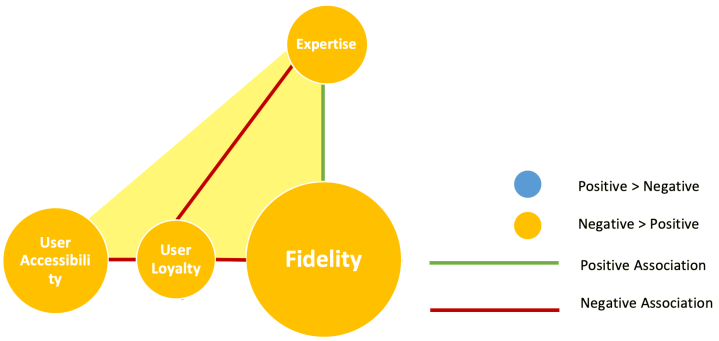


Fig. 5.6 Associations Between Expertise, User Loyalty and User Accessibility in Externalisation

However, some participants also acknowledge that more and more portable and affordable devices for Digital Sketching are available now that are embedded with their other daily used electronic devices; i.e., laptops like Surface Pro, tablets like iPad Pro, mobile

device add-ons like Wacom Smartpad, etc. Therefore, it is likely that User Accessibility of Digital Sketching in the industrial design field will be increased shortly, which could potentially lead to an increase in User Expertise and User Loyalty of this tool among future designers. If so, the current considerations around these DTCs would no longer be a barrier.

5.4.4 Associations of the Key DTCs of Digital Sketching in Externalisation

As a summary, the associations of the key DTCs suggested by the interview data in *externalisation* are illustrated in Figure 5.7, which forms a basis to further discuss the manifestation of Digital Sketching in *externalisation* in Chapter 7.

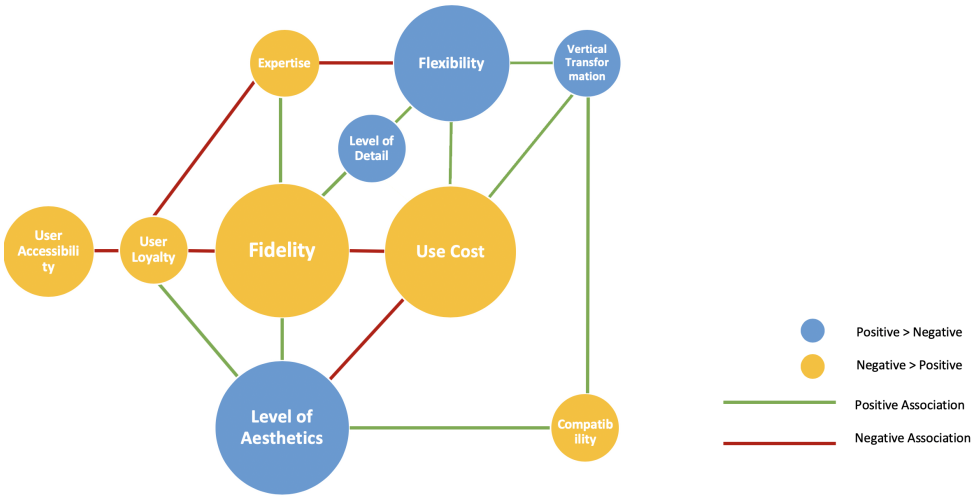


Fig. 5.7 Key DTCs of Digital Sketching in Externalisation

5.5 Key DTCs of Digital Sketching for External Communication

According to the designers' comments on the general design process (see interview questions of general information), there are normally two major *external communication* periods in their design projects. One is during the Early-Middle design phases where designers present and discuss their selected ideas with the clients for project sign-off. Most participants claim that regular updates and a pitch of the selected concepts are their general activities during this period. Another major *external communication* period is towards the end of a project where designers usually use high-resolution renderings and prototypes to present and sell their final designs.

In Figure 5.8, the most frequently mentioned Design Tool Characteristics (DTCs) of Digital Sketching in *external communication* are given, based on the interview data.

The sentiments on these key DTCs suggest that designers have an overall positive view of using Digital Sketching to communicate their designs with clients and other non-designer stakeholders. Interview data also suggest that designers' positive sentiments towards Digital Sketching focus on the earlier *external communication* period rather than the later one. This finding concurs with the current common use of Digital Sketching for beautifying traditional sketches before CAD, but the reasons behind this pattern of use are further explained by the key DTCs in this tool-use condition.

The key DTCs in *external communication* are **Level of Aesthetics, Use Cost, Ambiguity, Level of Commitment, Fidelity** and **Level of Detail**. Associations between these key DTCs are also identified from the data and presented in the following Subsections 5.5.1 and 5.5.2.

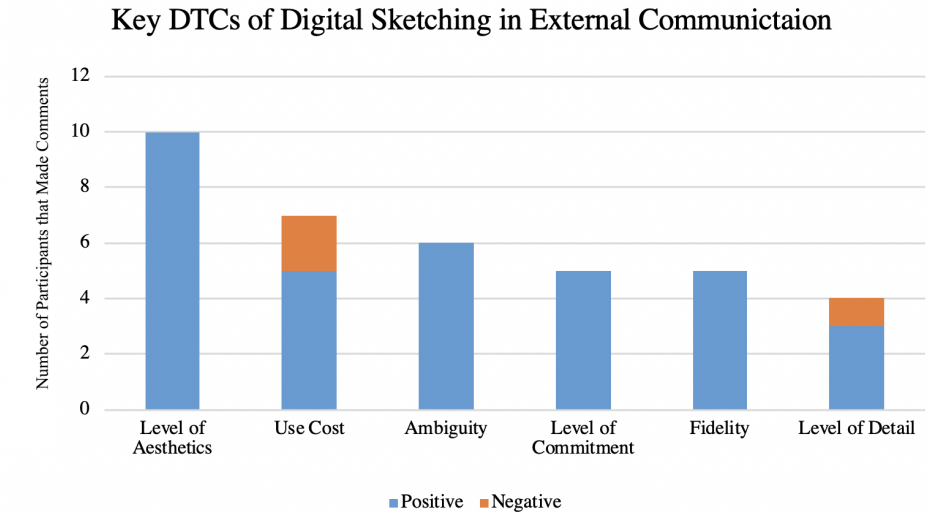


Fig. 5.8 Key DTCs of Using Digital Sketching for External Communication

5.5.1 External Communication: Ambiguity, Level of Commitment, Fidelity and Their Associations

The associations between DTCs in each tool-use condition are drawn based on whether the DTCs were mentioned together within the same comment to a question or not. Based on the interview data, Ambiguity, Fidelity and Level of Commitment (perceived by clients or other non-design stakeholders) are positively associated with each other in *external communication*. In other words, interview participants mention these three DTCs – together or with two of them in pairs – with positive sentiments. The pattern of this association is figuratively illustrated in Figure 5.9. Similar to Figures 5.4–5.7, the size of the circles in the Figures 5.9–5.11 reflects the number of references of the characteristics made in the interview data.

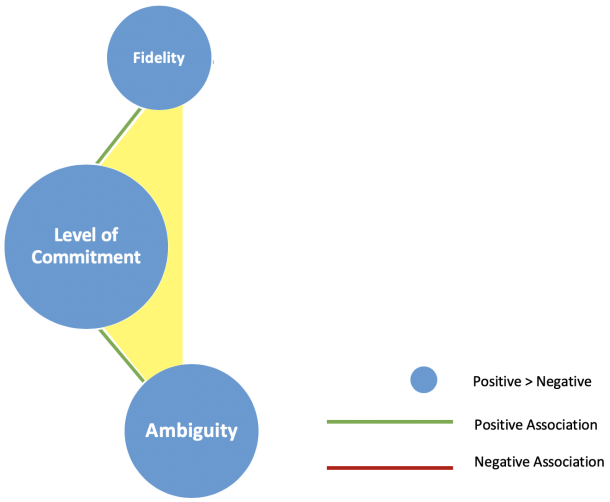


Fig. 5.9 Associations Between Ambiguity, Level of Commitment and Fidelity in External Communication

Designers indicate that when creating design representations to communicate with clients or stakeholders during the Early-Middle design phases, Sketching (both Digital and Traditional) is better for encouraging clients to participate. Specifically, designers show positive sentiments to both the Level of Commitment (6 out of 6 participants) and Ambiguity (5 out of 5 participants) with Digital Sketching in *external communication*. This is partially due to ambiguous sketches helping "ease" the ideas into the clients, and they feel less fixed or locked into one particular idea (Level of Commitment). Hence, they might offer more constructive feedback based on their interpretations of the sketches rather than jumping into acceptance or even rejection of the overall design. When provided with sketches, clients feel more comfortable to get involved in the design process and provide more feedback. For example, designers state that the Ambiguity of digital sketches can trigger the clients to reinterpret the ideas, "get their imagination going" (P7), and "they won't get distracted by small details that they don't like" (P11).

Apart from preserving the Ambiguity of the design, designers also show 5/5 positive sentiments towards the Fidelity offered by Digital Sketching in the Early-Middle phases in the design process. They admit their preference for using Digital Sketching to pitch the design ideas in the earlier *external communication*s. According to the interview participants, it demonstrates "positive progress" (P3) on the design development, and Digital Sketching also "transitions the idea from scribble to something a bit more understandable" (P5).

For example, participants suggest that designers or engineers are trained to read the abstract traditional sketches that are not necessarily readable for non-designers. However, Digital Sketching facilitates a higher level of Fidelity that allows the visualisations of

the ideas closer to the potential end products or designers' mental images. In other words, designers suggest Digital Sketching can help "ease the clients into the ideas" (P6) with its Fidelity to the design concepts.

At the same time, designers find that clients can get a message from the relatively ambiguous digital sketches that the design is "not yet finished" (P11). Digital sketches are "not quite as refined" (P3) or not quite fixed compared to the more polished end product, so clients intuitively know that the design is under development. This is important in the Early-Middle phases in *external communication*, where clients need to know that they are "not locked into a particular idea" (P10). The Level of Commitment triggered by viewing digital sketches enables the clients to further contribute to the design development rather than accepting or rejecting the ideas. It seems designers can have more constructive feedback from the clients with Digital Sketching in *external communication*, and clients can have a more appropriate understanding of the project's progress.

To summarise, interview data regarding *external communication* indicate that Digital Sketching could reserve space for designers to keep developing and refining the design and also stimulate constructive feedback from clients. Digital Sketching also facilitates a good level of Fidelity that conveys the design and project progress in an understandable and acceptable way to clients and stakeholders.

5.5.2 External Communication: Level of Aesthetics, Level of Detail, Use Cost, Flexibility and Their Associations

In *external communication*, participants also suggest there are associations between other key DTCs of Digital Sketching; namely, Level of Aesthetics, Use Cost, Level of Detail and Flexibility. When answering the interview questions regarding the use of Digital Sketching in *external communication*, these four DTCs were mentioned together by multiple participants. Figure 5.10 figuratively illustrates their associations and their sentiment results, based on the interview data. Designers suggest that the Level of Aesthetics provided by Digital Sketching could offer a good balance in terms of adding details to the design and maintaining the flexibility to modify it – both in a timely manner.

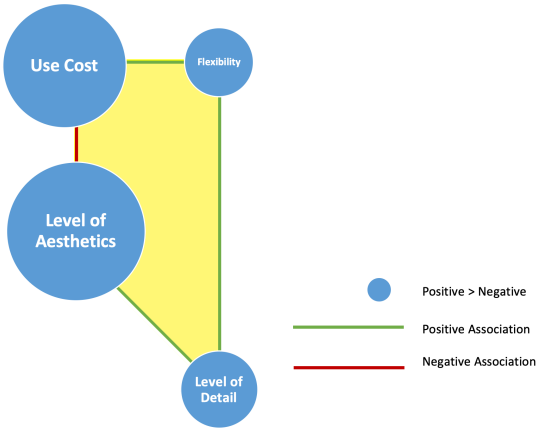


Fig. 5.10 Associations Between Level of Aesthetics, Level of Detail, Use Cost and Flexibility in External Communication

Specifically, participants have very positive sentiments towards the Level of Aesthetics offered by Digital Sketching in *external communication*. This characteristic was mentioned by the majority of the participants (10/12), all with positive feedback. They claim that Digital Sketching is "neat", "polished", "nice" and "more consistent". For example, participants comment that a polished digital sketch is "something that looks awesome" (P6), and "it would be a really nice way to present the design" (P1). The consistency facilitated by the digital sketching software in digital platforms and environments may contribute to the Level of Aesthetics. According to the interview data, the consistency may include but is not limited to colour schemes, line style, fonts and drawing styles. For instance, participants suggest that "to the clients, it [Digital Sketching] looks really consistent" (P1), and "a lot neater" (P11).

Level of Detail is one of the key DTCs usually mentioned together with Level of Aesthetics in this tool-use condition. Participants primarily show positive sentiments (3 out of 4 participants) towards the Level of Detail provided by Digital Sketching. This characteristic includes both Aesthetic Detail and Engineering Detail. Designers suggest that not only the aesthetic form/texture/pattern/colour details of the design can be conveyed easily with Digital Sketching but also some of the "mechanical needs" (P3). Participant 6 (P6, see Table 5.3) describes that "the client really get a feel for how different the design could look just with different colours and patterns applied...the way the surface read, the graphical breaks and materials, you can put all of that really well into a digital sketch".

At the same time, a consideration was mentioned regarding the Level of Detail in Digital Sketching. Interview data indicate that clients may tend to choose the design representations with a higher Level of Aesthetic Detail rather than the more suitable design solutions. Hence, the potential bias on digital sketches with a high Level of Aesthetics

and Level of Detail needs to be considered when evaluating the design concepts in *external communication*. Apart from that, interview data suggest Digital Sketching is a preferable way for *external communication* in the Early-Middle phases, which can be visually appealing with supporting design details to impress the clients and stakeholders.

Participants also show primarily positive sentiments toward both the Use Cost (5 out of 7 participants) and Flexibility (5 out of 5 participants) of Digital Sketching in *external communication*. The two negative comments on the Use Cost of Digital Sketching from the participants are associated with the designer's potential tendency or obsession to pursue a high Level of Aesthetics with this tool to please clients. Using Digital Sketching to conduct communication with clients is recognised as having low Use Cost and high Flexibility for shading/colouring/detailing (Level of Aesthetics and Detail). Use Cost was mentioned together with Level of Aesthetics by multiple participants in their answers to the same question in *external communication*, and Flexibility was mentioned together with Level of Detail. Designers also admit that the Use Cost of Digital Sketching is linked with their User Expertise of the tool. As an illustration, participant 11 (P11) says that "they [the experts in the team] can do digital presentation sketches really quickly". Apart from the influences from the User Expertise, participants indicate that using Digital Sketching can "achieve a high level of resolution really quickly" (P7) or, in a more comparative way, say that "CAD actually takes more time than Digital Sketching" (P8) for them to visualise the ideas for the clients.

Designers also suggest the Flexibility offered by Digital Sketching could contribute to reducing the Use Cost of this tool in *external communication*. For example, participant 7 (P7) mentions that "sliding the colour panel to generate different colour schemes for the design can be done in a few seconds". As the Use Cost of Digital Sketching is relatively low, participants also admit that one or a few expert digital sketchers in their team can usually do multiple sketches quickly for the team to save time, which also contributes to the Level of Aesthetic in terms of consistency in sketching styles. Hence, digital sketches can be made easier and clearer for clients to read and understand.

5.5.3 Associations of the Key DTCs of Digital Sketching in External Communication

Figure 5.11 illustrates the associations between the key DTCs in *external communication* discussed in this subsection. The interview results concur with the current use of Digital Sketching in practice as a beautifying tool during the middle design phase. The results also explain this pattern of use of Digital Sketching in this tool-use condition

with specific DTCs and their associations.

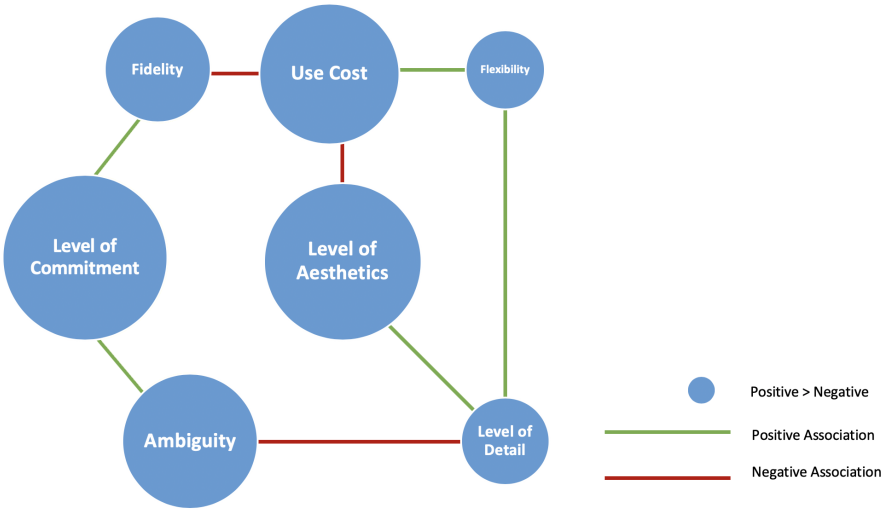


Fig. 5.11 Associations Between Key DTCs of Digital Sketching in External Communication

The interview data suggest that during the Early-Middle design phases, with less time investment, designers could use Digital Sketching to clearly convey their design ideas, reserve space for further design refinement, gain constructive feedback from clients and show more impressive and detailed design visualisations to keep the clients "happy".

5.6 Key DTCs of Digital Sketching for Internal Communication

Interview data suggest that using Digital Sketching for *internal communication* in industrial design is not commonly practised, considered or recognised. As is shown in Figure 5.12, the overall references for using Digital Sketching to communicate design ideas with team members or other designers and engineers are lower than the references in all the other tool-use conditions.

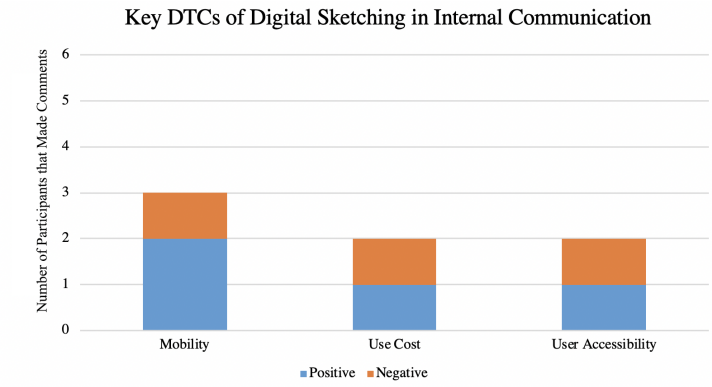


Fig. 5.12 Key DTCs of Using Digital Sketching for Internal Communication

Based on the limited data in this tool-use condition, there is no dominant attitude regarding its use suggested by the interviews. However, the references on using its neighbouring tools, especially Traditional Sketching, for *internal communication* are high (see Table 5.5). Therefore, the interview results of *internal communication* and discussion of the data are presented with comparisons in Subsection 5.9.3.

Visualisation Tool	**Participants Mentioned the Use / Total Participants**
Traditional Sketching	12 out of 12 Participants
Digital Sketching	4 out of 12 Participants
CAD Modelling	6 out of 12 Participants

Table 5.5 The Reference Ratio in the Interviews of Each Tool Being Used in Internal Communication

Three key DTCs of Digital Sketching in this tool-use condition are identified to first explore the reasons behind its lack of use. According to the interview participants, Mobility, Use Cost and User Accessibility are the main characteristics for them to consider when using Digital Sketching in *internal communication*.

Mobility of Digital Sketching includes the mobility of the tool itself and its resulting design representations/visualisations. Participants share different opinions about the Mobility of Digital Sketching and digital sketches. Some of them appreciate the convenience of digital sketches in that they are digital, easier to make copies, and more accessible in a certain way for the team, but they also recognise the printed hard copies of digital sketches are "more open" for a big group to go through the ideas. Participant 3 (P3) claims that "it [Digital Sketching] doesn't allow you the freedom to walk around and speak freely", and printed digital sketches are more suitable for group discussion unless "we have a beautiful tablet table and we can shuffle things around".

There are a few interactive panels in the market that can offer multiple people to interact and view documents digitally and cooperatively. But this brings up another concern about using Digital Sketching for *internal communication* – the User Accessibility.

User Accessibility of Digital Sketching focuses on the accessibility of the tool/device at the workplace. As participant 4 (P4) states, *internal communication* is about displaying the ideas to the team members to "get their input". Easy and equal access to the design representations among team members is vital for gaining effective advice. The cost of digital tablets for sketching and the cost of the interactive panel for display are the likely sources of negative sentiments in the interview data. The costs of both devices can significantly limit the User Accessibility. Participant 3 (P3) claims that an interactive panel "would be fantastic but it's not right here right now". However, more and

more design firms are starting to make Digital Sketching accessible to their designers. All three design firms that participated in the interviews are equipped with moderately sufficient Wacom tablets for Digital Sketching. One of them is equipped with a large interactive panel/table that is capable of displaying digital sketches and being operated by multiple people simultaneously.

Apart from Mobility and User Accessibility, participants also mention the Use Cost of Digital Sketching in this tool-use condition with both positive and negative sentiments. They notice that on the one hand, Digital Sketching can be more time-consuming compared with Traditional Sketching because they need to "go find a computer and open the digital program" (P11). On the other hand, it is a lot quicker than CAD. Further comparisons and discussions are given in Subsection 5.9.3.

5.7 Influences From the Learning Process of Digital Sketching

The data of Digital Sketching in the *learning process* offers a more comprehensive understanding of its current patterns of use in practice. The interview data suggest there could be long-term influences on the patterns of use of a tool from the designer's tool *learning process*. The six most frequently mentioned DTCs are identified as the key DTCs in the *learning process* condition (see Figure 5.13).

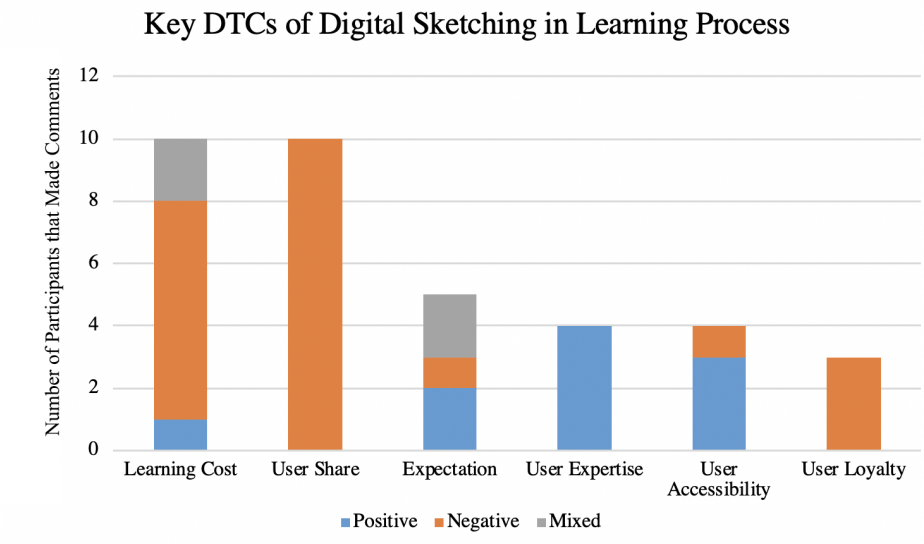


Fig. 5.13 Key DTCs of Learning and Early Use of Digital Sketching

According to the interview data, participants show primarily negative or mixed sentiments on the majority of these key DTCs of Digital Sketching; namely, **Learning Cost, User Share, Expectation** and **User Loyalty**. **User Expertise** and **User Accessibility**

are considered to have positive sentiments during the *learning process*.

5.7.1 Associations of the Key DTCs of Digital Sketching in the Learning Process

The associations between the key DTCs of Digital Sketching in the *learning process* are shown in Figure 5.13 and are discussed as follows. Learning Cost, User Share in education and designers' own Expectation of the learning outcomes are the most frequently mentioned characteristics of Digital Sketching when participants recall their *learning process* of this tool. Based on the results of the sentiment analysis, their attitudes toward these three key DTCs of Digital Sketching are primarily negative. A total of 7 out of 10 participants show negative sentiments of the Learning Cost of Digital Sketching; 10 out of 10 participants are not satisfied with the User Share of this tool and its learning resources in education; and 3 out of 5 participants are not positive about using it in meeting their Expectation. At the same time, they also suggest there are associations between these DTCs in the *learning process*. In Figure 5.14, how these characteristics were associated are figuratively illustrated based on how they were mentioned in the interview data. In both Figure 5.14 and Figure 5.15, the size of the circles represents the number of citations of the characteristics made in the interview data.

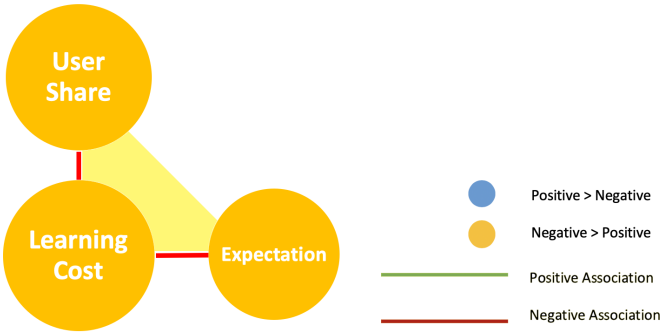


Fig. 5.14 Associations Between Learning Cost, User Share and Expectation in the Learning Process

Interview data suggest the Learning Cost of Digital sketching, especially for practising designers, is high. This is related to the low User Share of Digital Sketching in education in the past when most participants were trained in formal education. Most participants (10/12) claim that they had insufficient training at university, where training in Digital Sketching was only a component of one unit or one course rather than an individual course in which the skills could be better taught.

This low User Share in their formal education leads to the increase of Learning Cost later in their career. A total of 9 out of 12 participants, including those still using the tool

in their practice, admit that they had to treat Digital Sketching as a self-taught tool and learn it in their "spare time". As participant 1 (P1) explained, many of the participants "never got taught of it [Digital Sketching] at the university". They also suggest that the learning curve of Digital Sketching is regarded as psychologically "tricky", "tougher", "takes time/a while to get there" (P6), and many of them are "still learning and have spent countless hours" (P4) on improving their skills. One positive comment regarding the Learning Cost of Digital Sketching is from participant 11 (P11, see Table 5.3), who states that Digital Sketching is "a lot easier" to learn than traditional marker rendering in terms of colouring and shading.

In general, the skills of Digital Sketching are considered as "time-consuming" to learn and require "high maintenance" in terms of practising. This is also related to another finding in the interview data that the designers usually have high Expectation of the outcome or achievements from the *learning process*; namely, being able to generate high-quality digital sketches.

According to the interview data, the participants also have different sentiments towards using Digital Sketching in meeting their Expectation. Interview data suggest that their attitudes are affected by how high the Expectation is in terms of the quality of the design representations. For example, participants 5 and 9 (P5 and P9, see Table 5.3) have low Expectation and just want to "get the ideas across" with Digital Sketching, and who also find the *learning process* is easy and enjoyable. Participants 6 and 8 (P6 and P8) express their frustration with learning Digital Sketching as they have high Expectation. Based on the highly polished references on the internet, they know what they "could do" with Digital Sketching. However, it is hard to match that Expectation when learning Digital Sketching in their spare time.

In other words, since the tool itself opens up more possibilities, designers may feel stressed to achieve high-quality results and get frustrated on their journey to mastering the tool. According to the participants, exposure to high-quality digital sketches from a peer or the internet can cause stress during the *learning process*. Depending on how well the designers handle the "stress", it may turn into either motivation for continuous learning of the tool or a decision to terminate learning and using it. The *learning process* of Digital Sketching is revealed to be time-consuming without a good investment of resources in the formal education, and it can be more frustrating if designers have high expectation on achieving what the tool can offer.

Fortunately, more and more universities and institutions now offer training on Digital Sketching to their students. For example, according to the Digital Sketching tablets company (Wacom, 2018), the Wacom Authorised Training Centers (WATCs) within

institutions that incorporate Wacom tablets in their curriculum number in the high 50s in Australia and New Zealand alone. Therefore, learning Digital Sketching from formal education may be less of a concern in the near future. The Learning Cost of it could also be optimised by educators and institutions for future practising designers. Discussion on how the *learning process* of Digital Sketching influences its patterns of use in practice is given in Chapter 7.

Apart from these three key DTCs, three User-related Characteristics of Design Tools (UCs) are also recognised as key DTCs of Digital Sketching in the *learning process* based on their references in the interview data. In Figure 5.15, the associations between the six key DTCs of Digital Sketching in the *learning process* are figuratively illustrated. Different from what is expected, the interview data suggest that designers have less problem with achieving User Expertise in Digital Sketching if they have already mastered Traditional Sketching. A total of 4 out of 4 participants show positive attitudes towards the User Expertise of Digital Sketching in their *learning process*. Besides, having User Accessibility to the Digital Sketching device during the *learning process* is becoming more and more affordable, which is considered positive by 3 out of 4 participants. For example, participant 3 (P3, see Table 5.3) claims that the "the learning curve is less steep", and skills from Traditional Sketching are transferable to Digital Sketching; namely, "the motor skills to actually draw".

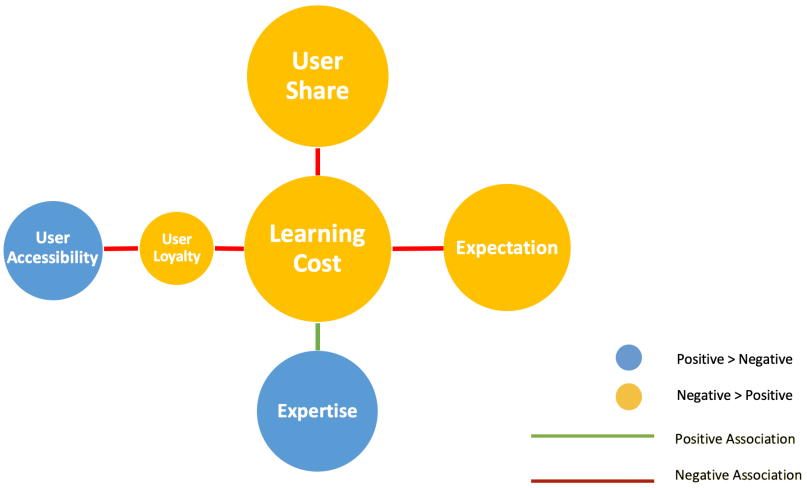


Fig. 5.15 Key DTCs of Learning and Early Use of Digital Sketching

However, the User loyalty towards the neighbouring tools of Digital Sketching, either Traditional Sketching or CAD, might become a prohibitive factor in learning this tool. Participants loyal to Traditional Sketching claim that they "don't see the benefits of doing that on the Wacom" (P1). Hence, learning Digital Sketching is not an appealing choice to advance their design practice. Participants also suggest that learning Digital

Sketching is “more challenging” when they are “so used to CAD” (P2).

The interview data suggest that devices and resources to learn Digital Sketching are becoming more and more accessible. User Expertise of its neighbouring tools can be a double-edged sword. Good User Expertise on Traditional Sketching may help with achieving good User Expertise of Digital Sketching. However, if the good User Expertise of the neighbouring tools turns into high User Loyalty, it may discourage designers from learning Digital Sketching.

5.8 Summary: The Key DTCs of Digital Sketching

In this study, the Design Tool Characteristics (DTCs) framework is used as an approach to identify and highlight the motivations and considerations of the designers when selecting and using different design tools in practice. In the interview analysis, participants' comments on the design tools are coded with the characteristics. The most frequently mentioned characteristics are considered as the key DTCs to further reveal the patterns of use of Digital Sketching during the Early-Middle phases in the industrial design process. This is because referring to a characteristic of a tool in the tool-use condition indicates that the designer considers its role in the design process and its influence on outcomes.

In Table 5.6, all the key DTCs of Digital Sketching across four tool-use conditions are listed. For each tool-use condition, there are different key DTCs with different priorities that form different associations. This also shows that designers have different motivations and considerations for each condition. According to the interview data, designers also have different attitudes towards Digital Sketching and its DTCs in different tool-use conditions. The attitudes of interview participants towards the key DTCs of Digital Sketching are also listed in Table 5.6, which can reflect designers' perception of the tool. It's worth noting that some characteristics are considered as the key DTCs in more than one tool-use condition, and some are even associated with different sentiments.

Conditions	Key DTCs	Total References (Unit: Person)	Positive	Negative	Mixed
Externalisation	Fidelity	6	1	3	2
	Level of Aesthetics	6	6	0	0
	Flexibility	5	5	0	0
	Use Cost	5	0	0	5
	User Accessibility	5	1	4	0
	Compatibility	5	0	0	5
	Vertical Transformation	4	4	0	0
	User Loyalty	4	1	3	0
	User Expertise	3	0	3	0
	Level of Detail	3	0	0	3
External Communication	Level of Aesthetics	10	10	0	0
	Use Cost	7	5	2	0
	Ambiguity	6	6	0	0
	Level of Commitment	5	5	0	0
	Fidelity	5	5	0	0
	Level of Detail	4	3	1	0
Internal Communication	Mobility	3	2	1	0
	Use Cost	2	1	1	0
	User Accessibility	2	1	1	0
Learning Process	Learning Cost	10	1	7	2
	User Share	10	0	10	0
	Expectation	5	2	1	2
	User Expertise	4	4	0	0
	User Accessibility	4	3	1	0
	User Loyalty	3	0	3	0

Highlighted DTCs are indicated as key DTCs in more than one tool-use condition

Table 5.6 Key DTCs of Digital Sketching in Industrial Design Practice

Use Cost is mentioned across the main tool-use conditions except for the *learning process*; this may indicate that the timely efficiency of using Digital Sketching is an important factor in practice that has kept the designers wary. Level of Aesthetics is mentioned in both *externalisation* and *external communication* as one positive key characteristic of Digital Sketching, which is in line with the current knowledge of the tool; namely, a beautifying tool. Fidelity appears as a negative key characteristic in *externalisation* but a positive characteristic in *external communication*. Level of Detail is also mentioned in these two tool-use conditions as a key characteristic.

Apart from these Capability-related Characteristics of Design Tools (CCs), there are also two User-related Characteristics of Design Tools (UCs) of Digital Sketching that occurred to the participants' minds in different tool-use conditions during the interviews. These are User Loyalty and User Expertise. This suggests that the level of the designer's expertise in Digital Sketching and whether one can easily gain skills in it or not are important factors. It could potentially influence the designer's decision on the selection and use of the tool. It also indicates that designers may develop an emotional relationship with the tools that they were taught or have been using. The selection of these tools can be developed from an initial user inertia as a convenience choice (i.e.,

learnt the tool at university) to then move on to perhaps consistent use as a rational choice at the workplace, hence leading to User Loyalty as an emotional engagement. However, the participants also admit that User Loyalty to one tool can inhibit the motivation to use or learn new tools. According to the interview data, some designers tend to keep using the tools that they are familiar with. Even with acknowledgement that the new tools could be a more rational choice in certain scenarios, User Loyalty could dominate the tool selection.

All in all, the interview data indicate that these DTCs of Digital Sketching (Table 5.6) are the key characteristics that designers generally consider during their daily practice. The participants have an overall positive attitude towards using Digital Sketching in *external communication*, but they don't show a dominant positive attitude towards using it in other tool-use conditions. This result is consistent with the current conservative use of Digital Sketching in practice as a tool for beautifying traditional sketches to impress the clients and stakeholders.

However, the current understanding of the patterns of use of Digital Sketching in industrial design is not necessarily comprehensive, which was the initial motivation of this study. As the interview results also concur with the potential use of Digital Sketching that is implied by the literature, discussion of the interview results are given in Chapter 7 to answer the research question 2. To give a more comprehensive understanding of the use of Digital Sketching in the Early-Middle phases, comparisons with the use of neighbouring tools follow.

5.9 Comparisons Between Digital Sketching and Traditional Sketching and CAD

In this section, comparisons are made between Digital Sketching and its neighbouring tools based on the interview data. The key Design Tool Characteristics (DTCs) of Digital Sketching under each tool-use condition and their sentiments towards the three tools are the basis to draw the comparisons. In this qualitative study, the numeric results of the interview references in the tables are used to highlight the differences between the tools, and hence guide the discussion rather than with quantitative evidence. This enables further reflection on the comparative strengths and barriers of Digital Sketching and generates a more contextualised understanding of the patterns of its use in practice. The results contribute to answering research questions 2 and 3. Research question 3 – whether Digital Sketching could be a "pathway" to ease the transition between its neighbouring tools or not – is discussed in Chapter 7, primarily based on the results of

the interview comparisons.

To be specific, positive sentiment towards a key characteristic of Digital Sketching might indicate hidden opportunities for utilising this tool. Similarly, negative sentiment towards the key DTCs can imply barriers surrounding the use of this tool in design practice. For example, participants are very positive about both the Level of Aesthetics and Use Cost of Digital Sketching in *external communication*. At the same time, its neighbouring tools either have negative Use Cost or negative Level of Aesthetics in this tool-use condition, which indicates an opportunity to utilise Digital Sketching for achieving more effective outcomes in a timely manner. Similarly, designers have negative feelings about the User Loyalty of Digital Sketching when comparing with Traditional Sketching and CAD in both the *learning process* and *externalisation*. This may indicate a potential barrier surrounding the use of Digital Sketching.

Therefore, the comparisons between Digital Sketching and its neighbouring tools in each tool-use condition are given as follows to reach a more comprehensive understanding of its patterns of use in practice.

5.9.1 Comparisons of Key DTCs Referenced With Respect to Externalisation

As is in Table 5.7, Digital Sketching shares two positive key DTCs with both Traditional Sketching and CAD in externalisation; namely, Level of Aesthetics and Vertical Transformation. Digital Sketching has the highest positive sentiment references on the Level of Aesthetics among the three tools based on the interview data. CAD has the highest positive references on Vertical Transformation due to the "adjusting and tweaking of details" (P6, see Table 5.3) that can be done with it. Digital Sketching and Traditional Sketching have a similar number of positive references on Vertical Transformation.

Tools / DTCs / Ref.	Digital Sketching				Traditional Sketching				CAD			
	Total	Positive	Negative	Mixed	Total	Positive	Negative	Mixed	Total	Positive	Negative	Mixed
Fidelity	6	1	3	2	10	5	1	4	10	7	3	0
Level of Aesthetics	6	6	0	0	4	4	0	0	5	5	0	0
Flexibility	5	5	0	0	4	4	0	0	7	2	4	1
Use Cost	5	0	0	5	12	12	0	0	12	3	3	6
User Accessibility	5	1	4	0	9	9	0	0	4	1	3	0
Compatibility	5	0	0	5	6	3	1	2	5	1	4	0
Vertical Transformation	4	4	0	0	4	4	0	0	5	5	0	0
User Loyalty	4	1	3	0	6	6	0	0	2	1	1	0
User Expertise	3	0	3	0	7	2	5	0	9	7	2	0
Level of Detail	3	0	0	3	10	1	1	8	11	10	0	1

Red colour is associated with negative sentiments, green colour is positive, orange colour is neutral (hereafter).

Table 5.7 References of Key DTCs in Three Tools Under Externalisation

Apart from these two DTCs, Digital Sketching and Traditional Sketching share another

two positive characteristics, which are Flexibility and Compatibility. The interview data also concurs with the results of the literature reviews in Chapters 1 and 3 that Digital Sketching has beneficial characteristics worth noting. In other words, Digital Sketching could be further utilised in practice and may ease the transitions between Traditional Sketching and CAD. For instance, participants suggest that Digital Sketching offers good Flexibility and reasonable Compatibility for integrating with other tools. It also starts offering better and better User Accessibility that is closer to Traditional Sketching. It facilitates good Vertical Transformation as well as good Level of Aesthetics compared to both Traditional Sketching and CAD. Discussions on how these positive key DTCs reflect the manifestation of Digital Sketching in practice are given in Chapter 7.

Figure 5.16 illustrates the sentiment results in absolute values, which are used to give a straightforward overview of the different natures of the tools. The number given to each characteristic is the absolute value of the sentiment results, which means it is calculated by the number of positive references minus the number of negative references. Since the mixed references mention both negative and positive aspects of the characteristic in one comment, they are considered to be self-neutralised to zero. The results of the interviews suggest that Digital Sketching also has three relatively negative key characteristics compared to both Traditional Sketching and CAD in *externalisation*, which are Fidelity, User Loyalty and User Expertise.

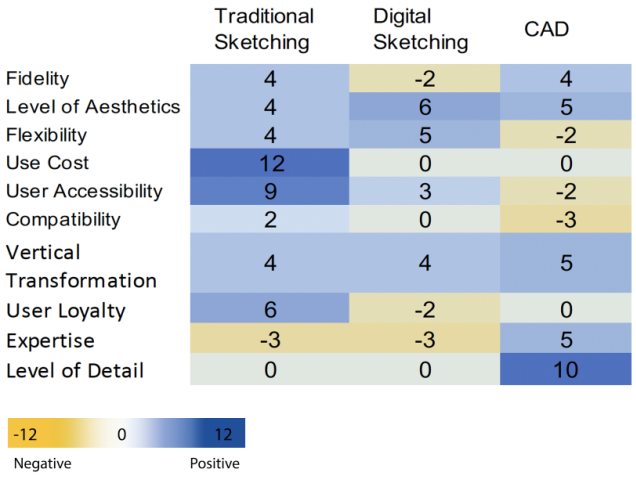


Fig. 5.16 Bridging Traditional Sketching and CAD in Externalisation

Participants show positive sentiments towards the Fidelity of Traditional Sketching in *externalisation*. According to their comments, Traditional Sketching only requires a rough idea (low Fidelity) to start working with, which also results in rough concept visualisations. Participants are also positive about the Fidelity of CAD in this tool-use condition because they can justify the requirement of a clear mental image (high

Fidelity) since the end visualisation can be high in Fidelity too. In some cases, participants mention the use of low Fidelity CAD models in the Early-Middle phases of the design process to guide the dimensions of the design. This innovative use of CAD lowers the requirement of Fidelity for CAD in the earlier phases and gains positive sentiments from the designers. The related techniques of this pattern of use of CAD have been widely mentioned by the participants in various terms; namely, "block CAD", "rough model" and "proxy CAD". Therefore, the interview data show participants are positive about the Fidelity of both Traditional Sketching and CAD while keeping a more wary attitude towards the Fidelity of Digital Sketching.

Designers also have more negative sentiments towards their User Expertise and User Loyalty of Digital Sketching compared to Traditional Sketching and CAD. As mentioned in Subsection 5.4.3, these two UCs are associated. According to the interview data, designers tend to have low User Loyalty for Digital Sketching, especially if their User Expertise of it is low. Some participants explained that they have no "interests" to "practise more" Digital Sketching.

When the participants were studying industrial design, most of their formal education institutions and universities offered more training on Traditional Sketching and CAD than Digital Sketching. This difference of User Share in education back then guaranteed that a certain level of User Expertise of those two tools was gained by the participants. Hence, this initial boost of expertise could potentially further influence designers' User Loyalty of the two tools and facilitate positive development between the relevant User Expertise and User Loyalty.

However, the sentiment results of these two key DTCs show that Traditional Sketching and CAD have a bipolarised nature. As illustrated in Figure 5.16, Traditional Sketching has positive User Loyalty, but it is difficult for designers to gain and maintain a good level of User Expertise even with a good User Share of formal training and courses in education. On the contrary, CAD has moderately positive User Loyalty, but it is easy for designers to develop User Expertise of CAD once they pass the initial steep learning curve. Even though the interview data show negative sentiments towards both DTCs of Digital Sketching at the moment, it could become more positive as more and more training of this tool in education is available.

Besides, Digital Sketching receives moderately positive sentiments towards both Use Cost and Level of Detail in *externalisation* while Traditional Sketching and CAD show more bipolarised sentiments on these two characteristics. As designers claimed, they are aware of the limited Level of Detail that Traditional Sketching can offer so they do not spend extra time (low User Cost) on it to attempt a high Level of Detail. Designers

also suggest that the Use Cost of CAD is relevant to the resulting Level of Detail, but they consider CAD has high Use Cost in general. For example, in the 6 references of mixed sentiment on CAD's Use Cost in *externalisation*, most of the participants acknowledge that they can lower the Use Cost by creating "rough models" with a lower Level of Detail. These "basic CADs" can be used for dimension guidance in the Early-Middle design phases. However, participants also expressed concerns about spending a lot more time "detailing in CAD". As discussed in Subsection 5.4.2, Level of Detail of Digital Sketching is also associated with its Use Cost for *externalisation*. As it appears to influence the decision of tool use and selection, this association in Digital Sketching and its neighbouring tools is selected to be further examined with observations. The results are presented in Chapter 6.

In Table 5.8, other frequently mentioned DTCs of Traditional Sketching and CAD in *externalisation* are listed. It shows that for Digital Sketching to be utilised in *externalisation*, there are more characteristics to pay attention to other than its own key DTCs. Accordingly, opportunities and barriers revealed by the missing attention on these DTCs of Digital Sketching in this tool-use condition can be further explored. For example, Accuracy of Traditional Sketching is highlighted with negative sentiments in Table 5.8(a) but with extreme positive sentiments (11/12) towards CAD in Table 5.8 (b). It might be essential to understand what level or range of Accuracy can be offered by Digital Sketching in *externalisation* to explore its comparative use.

Other Key DTCs of Traditional Sketching in Externalisation				
	Total	Positive	Negative	Mixed
*Accuracy	3	0	3	0
*Ambiguity	4	4	0	0
*Lateral Transformation	9	9	0	0
*Problem Re-framing	7	7	0	0
Immediacy	6	5	0	1
Expectation	6	2	4	0
User Share	5	5	0	0
Amount of Representations	6	6	0	0

* Shared DTCs between Traditional Sketching and CAD

(a)

Other Key DTCs of CAD in Externalisation				
	Total	Positive	Negative	Mixed
*Accuracy	11	11	0	0
*Ambiguity	5	5	0	0
*Lateral Transformation	5	1	1	3
*Problem Re-framing	6	4	1	1
Emotional Commitment to the Idea	9	3	5	1
Holistic View of the Object	8	8	0	0
Tendency to Mix Tools	10	10	0	0
Level of Commitment	8	7	1	0

(b)

Table 5.8 Other Key DTCs of Traditional Sketching (a) and CAD (b) in Externalisation

Similarly, it suggests that designers view Ambiguity, Lateral Transformation and Problem-reframing of both Traditional Sketching and CAD in this tool-use condition with positive sentiments. It is important to understand how these DTCs of Digital Sketching influence its use in practice; that is, whether to match or compete with Traditional Sketching and CAD.

Apart from these four shared DTCs between Traditional Sketching and CAD, the exclusive key characteristics of these two tools show other aspects to consider when using Digital Sketching in *externalisation*. For instance, the negative sentiments towards the

Expectation of Traditional Sketching and the Emotional Commitment to the idea of CAD can imply opportunities for Digital Sketching. The high number of references and positive sentiments towards Immediacy and Amount of Representations in Traditional Sketching suggests that designers consider these characteristics in this tool-use condition, and that they are happy with what Traditional Sketching can offer. These could be areas where Digital Sketching can improve to facilitate better *externalisation*. Similarly, strong references and positive sentiments towards Holistic View of the Objects and Tendency to Mix Tools of CAD show designers' potential preferences. In other words, Digital Sketching can be considered as offering good support on these DTCs to facilitate its use in *externalisation*.

Further discussion on the manifestation of Digital Sketching in *externalisation* is given in Chapter 7.

5.9.2 Comparisons of Key DTCs Referenced With Respect to External Communication

As is shown in Table 5.9, designers show an overall positive sentiment towards using Digital Sketching in *external communication*. Some concerns of using Traditional Sketching and CAD for *external communication* during the Early-Middle design phases were also expressed.

Tools / DTCs	Digital Sketching				Traditional Sketching				CAD			
Ref.	Total	Positive	Negative	Mixed	Total	Positive	Negative	Mixed	Total	Positive	Negative	Mixed
Level of Aesthetics	10	10	0	0	7	0	3	4	9	9	0	0
Use Cost	7	5	2	0	4	3	1	0	5	2	0	3
Ambiguity	6	6	0	0	7	4	3	0	0	0	0	0
Level of Commitment	5	5	0	0	3	3	0	0	7	0	6	0
Fidelity	5	5	0	0	2	0	2	0	5	5	0	0
Level of Detail	4	3	1	0	1	0	1	0	6	5	0	1

Table 5.9 References of Key DTCs in Three Tools Under External Communication

Digital Sketching shares four key DTCs with Traditional Sketching in *external communication*, which are Level of Aesthetics, Use Cost, Ambiguity and Level of Commitment. In these four key DTCs, both Digital Sketching and Traditional Sketching attain dominantly positive sentiments towards Use Cost, Ambiguity and Level of Commitment. This indicates that Digital Sketching and Traditional Sketching as Sketching tools have low Use Cost in *external communication*, reserve an appropriate level of Ambiguity and offer a low Level of Commitment. This combination could benefit designers in the continuous development of a design idea and gain constructive feedback from the clients and non-designer stakeholders.

Digital Sketching also has very positive sentiment feedback on the Level of Aesthetics in this tool-use condition, which is similar to CAD. At the same time, designers show concerns towards the Level of Aesthetics of Traditional Sketching; more use of Digital Sketching for its Level of Aesthetics can be seen in practice. In other words, this result concurs with the current use of Digital Sketching for beautifying traditional sketches.

According to the interview data, Fidelity and Level of Detail of Traditional Sketching were not frequently mentioned by the participants, which is quite opposite to Digital Sketching. It indicates that designers have different priorities to care about when using different tools to communicate with clients and stakeholders. However, some participants expressed concerns about not being able to effectively convey the design to the clients with Traditional Sketching in a timely manner. Participants describe the Level of Detail, Use Cost and Fidelity of Traditional Sketching as "extremely time-consuming to sketch down all the details" (P9), and it is "not good enough to get what I am trying to get across to the clients" (P5). Meanwhile, designers show really positive sentiments towards these DTCs of Digital Sketching.

CAD shares most of the key DTCs with Digital Sketching in *external communication* except for Ambiguity. Table 5.9 shows that among the five shared key DTCs, Digital Sketching and CAD both have positive sentiment feedback on Level of Aesthetics, Fidelity and Level of Detail. This indicates that both Digital Sketching and CAD are offering appropriate support to the designers to achieve good Level of Aesthetics and Level of Detail to communicate the design clearly (Fidelity) with the clients. However, CAD has relatively negative sentiment results on its Use Cost and Level of Commitment compared with Digital Sketching. In other words, the use of CAD for *external communication* during the Early-Middle phases is considered to be time-consuming and could lock both designers and clients into unwanted premature design solutions or concepts.

All in all, the sentiment result of each key characteristic in *external communication* is calculated and presented in Figure 5.17. To give an overview of the data, the number given to the characteristic is the absolute value of the sentiment results. Therefore, the number is theoretically ranged from -12 to 12. In Figure 5.17, the key DTCs of Digital Sketching seem to offer positive possibilities to bridge the bipolarised differences between Traditional Sketching and CAD, like a jigsaw piece, which may benefit the *external communication* in the Early-Middle phases in industrial design practice.

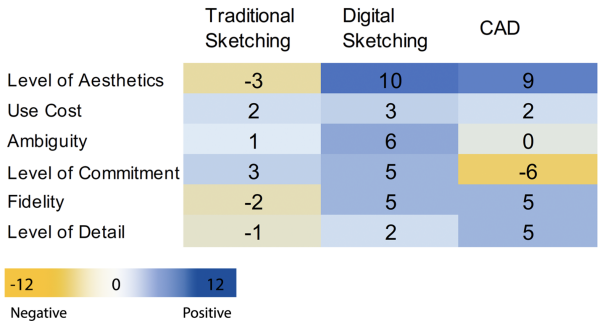


Fig. 5.17 Bridging Traditional Sketching and CAD in External Communication

Further discussion on the manifestation of Digital Sketching – namely, the patterns of use – are given in Chapter 7. Similarly, whether Digital Sketching could be a "pathway" to ease the troublesome transitions between its neighbouring tools or not is also discussed in Chapter 7 based on the interview and observation results.

5.9.3 Comparisons of Key DTCs Referenced With Respect to Internal Communication

According to the interview results, the overall comments on *internal communication* are less than all the other three tool-use conditions. It may indicate that designers pay more attention to tool selection and use when it comes to *externalisation* and *external communication*. Traditional Sketching is mentioned most frequently as a tool for communicating with other designers or teammates. Within the limited overall references in *internal communication*, the number of references on using Digital Sketching in this condition is the least among the three tools in this study. The number of references on the three key DTCs of Digital Sketching across the three tools is given in Table 5.5. Comparisons are made between Digital Sketching, Traditional Sketching and CAD, as they may help to reveal the current pattern of use in *internal communication* and the reasons behind it.

Table 5.10 shows that Digital Sketching shares all 3 key DTCs in *internal communication* with Traditional Sketching. Sentiment results of Traditional Sketching in this tool-use condition are more positive than both Digital Sketching and CAD. It indicates that when using Sketching tools for *internal communication*, designers tend to consider Use Cost; Mobility of the tool and representations; and User Accessibility to the tool.

Tools / DTCs	Digital Sketching				Traditional Sketching				CAD			
Ref.	Total	Positive	Negative	Mixed	Total	Positive	Negative	Mixed	Total	Positive	Negative	Mixed
Mobility	3	2	1	2	6	6	0	0	3	3	3	0
Use Cost	2	1	1	0	7	7	0	0	2	2	0	0
User Accessibility	2	1	1	0	4	4	0	0	1	1	0	0

Table 5.10 References of Key DTCs in Three Tools Under Internal Communication

With respect to these three characteristics, Traditional Sketching receives predominantly positive sentiments from the participants. For example, participants describe it as "the most convenient" and "fastest" as they can "sit together and look at all the sketches" (P3) and "work simultaneously".

Surprisingly, the Mobility and Use Cost of CAD are also considered positively by the interview participants. As participants explained, they can easily "print out the model renderings and pass around them to everyone" (P10) in the team. The time spent on building the CAD models is happily justified as the resulting visualisations can "provide more 3D details to the engineering team" (P3).

Since there are only three key DTCs of Digital Sketching identified in *internal communication*, other frequently mentioned DTCs in Traditional Sketching and CAD may help to reveal more about what motivates designers' selection and use of tools in *internal communication*. It may also indicate how Digital Sketching can contribute to *internal communication* in the future or be improved.

Table 5.11 shows that designers tend to consider these DTCs of Traditional Sketching in *internal communication*; that is, Fidelity, Problem-reframing, Vertical Transformation and Flexibility. It shows a few things that designers care about, and what they can do or not do with the tool. First, designers want to convey their mental images or ideas (Fidelity) to each other. Based on the interview data, they also want to stimulate more input and gain new perspectives (Problem-reframing) from others, decide and further develop the details of the concepts (Vertical Transformation), and easily modify the concepts in the group meetings or in-team conversations (Flexibility).

Other Key DTCs of Traditional Sketching in Internal Communication				
	Total	Positive	Negative	Mixed
Fidelity	4	4	0	0
Problem-reframing	4	4	0	0
Vertical Transformation	4	4	0	0
Flexibility	3	3	0	0
Level of Aesthetics	3	3	0	0

Other Key DTCs of CAD in Internal Communication				
	Total	Positive	Negative	Mixed
Level of Detail	4	4	0	0
Ambiguity	3	3	0	0

Table 5.11 Other DTCs of Traditional Sketching and CAD in Internal Communication

Based on the interview data, Digital Sketching has not been well-accepted or recognised in *internal communication* even though the tool is becoming more and more mobile and

accessible. Similar to Digital Sketching, CAD is not very well accepted and used in *internal communication*. However, two characteristics of CAD (see Table 5.11), Level of Detail and Ambiguity, are mentioned as positive and contributing characteristics by the interview participants. A total of 4 out of 12 participants show positive sentiments towards the Level of Detail, especially the Engineering Detail, offered by CAD in *internal communication*, and 3 out of 12 participants are happy with the low Ambiguity CAD models when passing the project to the "engineering team". As an example, participant 3 (P3, see Table 5.3) states that a basic CAD model works better than a sketch for this in-team communication as "they (the engineers) couldn't get enough details from the 2D sketch", but they can get a clear understanding of the design from a CAD model.

The frequently mentioned DTCs of Traditional Sketching and CAD in *internal communication* show some aspects that the designers might consider when choosing a tool (and the representations generated from the tool) to communicate within their team. These characteristics with respect to Digital Sketching may need to change if Digital Sketching is to be more widely used in *internal communication*.

5.9.4 Comparisons of Key DTCs Referenced With Respect to the Learning Process

As discussed in Section 5.7, it seems that the *learning process* of Digital Sketching can influence the patterns of its use in practice. Table 5.12 brings the sentiment results of its neighbouring tools in this tool-use condition into the discussion and comparison. It's worth noting that these characteristics are the key DTCs of Digital Sketching in the *learning process*.

Tools / DTCs	Digital Sketching				Traditional Sketching				CAD			
Ref.	Total	Positive	Negative	Mixed	Total	Positive	Negative	Mixed	Total	Positive	Negative	Mixed
Learning Cost	10	1	7	2	10	2	6	2	11	4	7	0
User Share	10	0	10	0	9	7	1	1	7	5	0	2
Expectation	5	2	1	2	3	1	0	2	0	0	0	0
User Expertise	4	4	0	0	2	0	2	0	4	3	1	0
User Accessibility	4	3	1	0	0	0	0	0	3	2	1	0
User Loyalty	3	0	3	0	4	4	0	0	4	4	0	0

Table 5.12 References of Key DTCs in Three Tools Under Learning Process

As is in Table 5.12, participants show both positive and negative sentiments towards the learning process of these three tools. Among the six key DTCs, three tools all have 2 to 3 DTCs associated with positive sentiment results. However, it is not saying that designers have similar attitudes towards the learning process of Digital Sketching and its neighbouring tools. The characteristics with positive feedback are different in one tool to another. Figure 5.18 illustrates the absolute value of the sentiment results of

the three tools in the *learning process*. It indicates that the participants have a slightly higher level of negativity towards the learning of Digital Sketching than Traditional Sketching and CAD.

First of all, participants report that the User Share of Digital Sketching was too low during their university years or early career years (around 2010–2015) for most of them to make a valid commitment to study and use it. They also suggest that the User Share of both Traditional Sketching and CAD in formal education and industry has been high enough in the industrial design field for them to formally learn the tools in their degrees and continuously use them in their careers. This finding may also help explain the relatively more positive sentiments in User Loyalty of Traditional Sketching and CAD than for Digital Sketching among the participants. Besides, the User Accessibility of Traditional Sketching and CAD in the *learning process* did not even cross the participants' minds, as these two tools are considered standard in industrial design and have high User Share in both education and industry.

As an overview in Figure 5.18, participants show negative sentiments towards the Learning Cost for all three tools. This is primarily based on the perception that these tools are time-consuming to learn, practise and master. In other words, the time factor of the Learning Cost of Traditional Sketching, Digital Sketching and CAD is high. However, the mental stress factor of the Learning Cost shows different levels for different tools. Surprisingly, among 9 participants that commented on the psychological Learning Cost of CAD, 5 of them show positive sentiments towards this characteristic of CAD. This is because the difficulties in learning CAD were only experienced "in the beginning" of the process. As discussed in Section 5.7, Digital Sketching was mostly self-taught according to the participants who also experienced mental stress apart from the time invested.

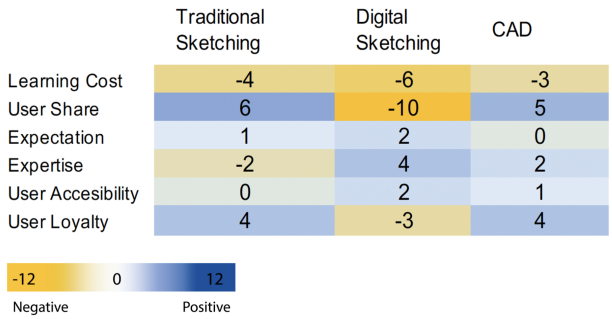


Fig. 5.18 Absolute Sentiment Values of Traditional Sketching, Digital Sketching and CAD in Learning Process

However, in terms of achieving a certain level of User Expertise and meeting their

Expectation, designers show more positive sentiments towards Digital Sketching than its neighbouring tools. For example, participants claim that their skills of Traditional Sketching are "just not good enough to get the idea 100% across" (P5), or it "took years to feel confident about" (P4) their Traditional Sketching or CAD. It suggests that learning Digital Sketching might not be as frustrating as some designers imagined, and it might be easier for designers to maintain their skills with digital design visualisation tools. In this study, participants consider the maintenance of Digital Sketching and CAD skills to be easier than Traditional Sketching as they have technology aids and they are not 100% doing manual operations.

For instance, many designers admit that it is "easier" to learn and master Digital Sketching because skills from Traditional Sketching are "transferrable". Also, Digital Sketching offers more possibilities to meet their Expectation of the resulting design visualisations. For example, Figure 5.19 shows the adjustable curve ruler in one of the Digital Sketching applications (Sketchbook Pro) on an iPad platform that can help designers sketch curve lines more accurately and neatly. This means it could be easier to learn and use Digital Sketching due to these helpful features.

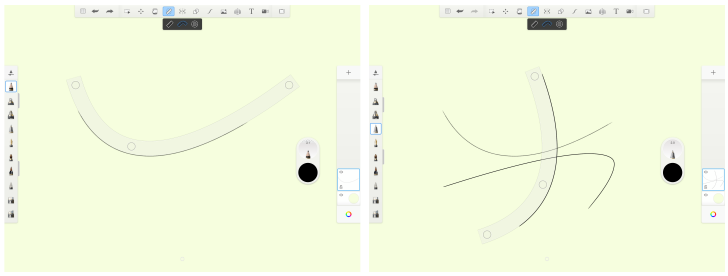


Fig. 5.19 Curve Rulers in Sketchbook Pro (iPad Version 2020)

According to the interview results, the *learning process* of Digital Sketching is not necessarily more frustrating or more time-consuming than its neighbouring tools. On the contrary, Digital Sketching might have a gentler learning curve to master, require low maintenance on the skills, and result in more satisfying design visualisations to meet the expectations. With the increase in User Share and User Accessibility of Digital Sketching in both education and industry, the influences from the *learning process* of Digital Sketching on its patterns of use in practice could be more and more positive in the near future.

5.10 Associations Between Key DTCs in Different Tool-use Conditions

As discussed in the above sections, many of the Design Tool Characteristics (DTCs) are suggested to be associated with each other and may have certain influences on the others. The associations among the key DTCs are defined by how frequent they were mentioned together in one comment to a question for a one tool-use condition regardless of the sentiments. Using a comment from the interview data as an example to illustrate how associate DTCs are identified, participant 1 (P1) states "I'm probably not the strongest person on working on a tablet, just because I've never been taught that", which suggests an association between the User Expertise and User Share in *externalisation*. This association between these two characteristics is also coded as a one-degree linkage since the participant directly mentioned it.

In this section, the associations between key DTCs for three major tool-use conditions are proposed based on interview data across the three tools. These are given as an overview of the interview results. These potential associations also facilitate further exploration of the motivations and concerns behind tool selection and use for each tool-use condition.

5.10.1 Associations of Key DTCs in Externalisation

According to the interview results in Table 5.13, industrial designers value Use Cost, Fidelity and Level of Detail the most when they use Traditional Sketching, Digital Sketching and CAD in *externalisation*. The heavy attention to these three DTCs is understandable since the general goal of *externalisation* is about effectively getting the designer's mental image to the physical world.

References / DTCs	Digital Sketching	Traditional Sketching	CAD	Total
Fidelity	6	10	10	26
Level of Aesthetics	6	4	5	15
Flexibility	5	4	7	16
Use Cost	5	12	12	29
User Accessibility	5	9	4	18
Compatibility	5	6	5	16
Vertical Transformation	4	4	5	13
User Loyalty	4	6	2	12
User Expertise	3	7	9	19
Level of Detail	3	10	11	24

Table 5.13 Key DTCs in Externalisation

Fidelity represents how close the design visualisations match the mental images. The interview results also suggest the Fidelity of the design visualisation tools could be tightly associated with the Level of Detail, Use Cost and Level of Aesthetics as discussed in both Subsections 5.4.4 and 5.9.1.

In Figure 5.20, associations among the DTCs in *externalisation* are proposed and figuratively illustrated based on the interview results of the three tools in this study. The associations are proposed for future examination and exploration of the characteristics of design visualisation tools.

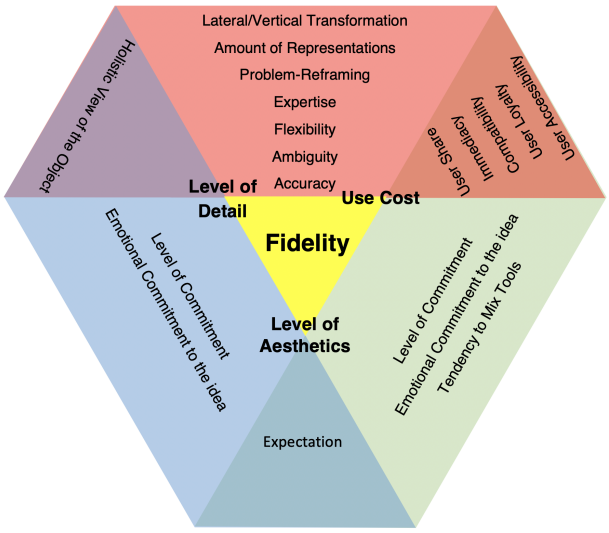


Fig. 5.20 A Map of Key DTCs in Externalisation

In this study, only the direct associations are supported by references in the interview data; namely, the associations shown as 1-degree adjacent between characteristics in Figure 5.20. The two-degree adjacent associations are hypothesis based on the interpretation of the interview data, but not yet tested. For example, discussion of the associations between Expectation and Level of Aesthetics, Tendency to Mix tools or Level of Commitment are within the scope of this study, while the associations between Expectation and Fidelity are neither supported by sufficient data nor further explored. The diagram is used to lead the discussion in Chapter 7 and inspired the design of the following observation experiment.

Proposing this diagram in this study aims at encouraging more research into the associations of DTCs in this tool-use condition, which will help designers to select and use appropriate tools for achieving effective design outcomes in a timely manner. In practice or education, this diagram could raise awareness and guide designers to monitor and modify their tool-use behaviours in *externalisation*. For example, if a designer/design

team is aiming to regulate the Use Cost in *externalisation*, the associated DTCs can be used to evaluate the problem as variables and shed light on appropriate solutions. In this example, as suggested by the diagram, potential solutions could be more training to improve User Expertise of the designer, granting better User Accessibility of the tools, or adjusting the designer's Level of Commitment to the design ideas.

5.10.2 Associations of Key DTCs in External Communication

As is shown in Table 5.14, the most frequently mentioned DTCs of the three tools in *external communication* is Level of Aesthetics. This is understandable as designers may want to impress the clients and present their profession in this tool-use condition using highly polished design visualisations. The other key DTCs are mentioned in similar frequency from 11 to 16 in total among the three tools.

References / DTCs	Digital Sketching	Traditional Sketching	CAD	Total
Level of Aesthetics	10	7	9	26
Use Cost	7	4	5	16
Ambiguity	6	7	0	13
Level of Commitment	5	3	7	15
Fidelity	5	2	5	12
Level of Detail	4	1	6	11

Table 5.14 Key DTCs in External Communication

Different from *externalisation*, the diagram of associated Design Tool Characteristics (DTCs) for *external communication* is arranged around Level of Detail, which is not necessarily the most frequently mentioned characteristic but one of the most interlinked DTCs in this tool-use condition (see Subsection 5.5.3). As designers are aiming to convey their full design ideas to clients or other non-designer stakeholders in *external communication*, the Level of Detail supported by the visualisation tools can play an arguably important role to convey the design ideas.

According to the interview results, participants also consider Level of Aesthetics, Use Cost and Level of Commitment as the important DTCs when they use Traditional Sketching, Digital Sketching and CAD in *external communication*. All these three DTCs are frequently referenced together with Level of Detail. For example, participants state: "To the client, you want it to look more finished [Level of Commitment] and professional [Level of Aesthetics], and detail it a little bit more [Level of Detail]"; and "Hand sketching would be extremely time-consuming [Use Cost] to me to sit down and try to sketch down all the details [Level of Detail] that I want to communicate".

Therefore, the associations of key DTCs in this tool-use condition are proposed and illustrated in Figure 5.21 centralised around Level of Detail and these three DTCs.

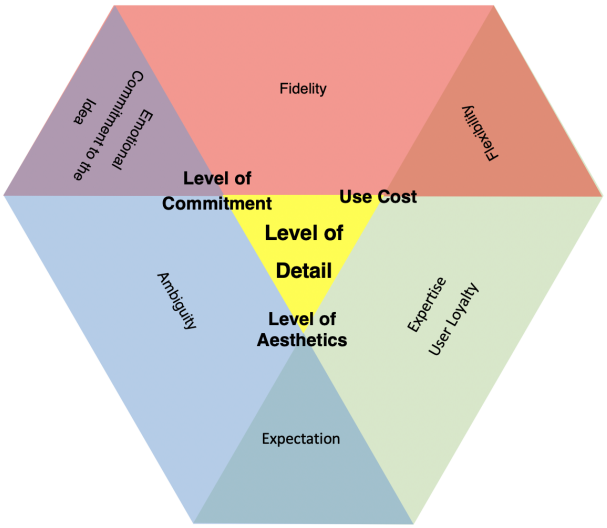


Fig. 5.21 A Map of Key DTCs in External Communication

Similar to Figure 5.20, only direct associations (one-degree adjacent on the diagram) in Figure 5.21 are proposed and supported by the interview data. It is used to lead the discussion in Chapter 7 and inspired the design of the following observation experiment. However, the diagram could also be able to offer some advice to design tool users to monitor and moderate tool-use behaviours in *external communication*. For instance, if a designer/design team is aiming to increase the Level of Aesthetics during *external communication*, the associated DTCs could be used as approaches to do so; i.e., improve the User Expertise of the designer, offer abundant Level of Detail in the visualisations and pay attention to the Ambiguity of the resulting visualisations.

5.10.3 Associations Between Key DTCs in Internal Communication

In *internal communication*, Mobility and Use Cost are suggested as the most interlinked DTCs among the uses of Traditional Sketching, Digital Sketching and CAD, as the interview results show in Table 5.15. Participants suggest Use Cost is the most interlinked characteristic in this tool-use condition (see Sections 5.6 and Subsection 5.9.3). Four groups of DTCs are associated with the Use Cost in *internal communication* as is illustrated in Figure 5.22. The DTCs in each group are also associated with other DTCs within their own group. For example, participants appreciate the Mobility of Traditional Sketching, which also contributes to their positive sentiments towards the

User Accessibility of this tool. As an example, designers can easily carry a sketchbook around which increases their chance to use this tool in their workplace and in other unusual working scenarios; e.g., in a Cafe during a meeting or at a co-worker's desk.

References / DTCs	Digital Sketching	Traditional Sketching	CAD	Total
Mobility	3	6	3	12
Use Cost	2	7	2	11
User Accessibility	2	4	1	7
Fidelity		4		4
Problem-reframing		4		4
Vertical Transformation		4		4
Flexibility		3		3
Level of Aesthetics		3		3
Level of Detail			4	4
Ambiguity			3	3

Table 5.15 Key DTCs in Internal Communication

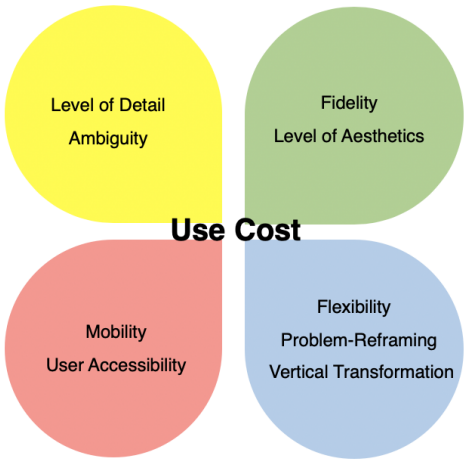


Fig. 5.22 A Map of Key DTCs in Internal Communication

As such, to guide the use of design tools in *internal communication* or improve a tool for more effective *internal communication*, the DTCs in Figure 5.22 may merit attention from the designers and design tool developers. As the use of Digital Sketching in this tool-use condition is noticeably low according to the interview results, further discussions around potential approaches to improve the situation are given in Chapter 7.

5.11 Reliability and Limitations of the Interview Results

Iterative coding of qualitative data method was adopted to ensure the reliability of the results (Saldaña, 2015). As a qualitative study, the inter-rater reliability method assesses the reliability of the interview coding scheme, which in return ensures the reliability of results. A total of 48 interview comments, which cover 2 references for each tool characteristic (24 in total) and 3–4 references for each participant (12 in total), were selected as the data sample for the reliability measurement. As shown in Appendix E, the distribution of the sample data across the three tools and four tool-use conditions is also similar to the overall data distribution. An independent coder, who is familiar with the definition of the Design Tool Characteristics (DTCs) framework, was chosen for the inter-rater reliability test to reduce the sources of unreliability (Raymond, 1992). Percentage agreement was used to calculate the resulting reliability (Belotto, 2018).

Three coding categories are measured for reliability; namely, the tools, the tool-use conditions and the characteristics. Table 5.16 lists the final results of the reliability measurement in tools, which has an overall agreement of 1. This category is used to measure how accurately the interview comments were mapped to the associated design visualisation tools. The agreement between the researcher and the independent coder is 100%.

Tools	Author	Independent Coder	Agreement
Traditional Sketching	12	12	1
Digital Sketching	16	16	1
CAD	20	20	1
			3/3 = 1

Table 5.16 Reliability of Interview Coding (Category 1: Tools)

Table 5.17 shows the results of the reliability measurement regarding tool-use conditions, which also has an overall agreement of 1. This category is designed to measure the reliability of the coding in mapping the comments to the tool-use conditions. The agreement between the researcher and the independent coder is 100%.

Tool-use Conditions	Author	Independent Coder	Agreement
Externalisation	33	33	1
External Communication	7	7	1
Internal Communication	4	4	1
Learning Process	4	4	1
			4/4 = 1

Table 5.17 Reliability of Interview Coding (Category 2: Tool-use Conditions)

Similarly, Table 5.18 shows the initial overall reliability measurement of the interview coding, which is 0.86. As per recommendations for this type of coding (Saldaña, 2015), mediation was arranged with the independent coder to refine the coding scheme and improve agreement and thus reliability. After the discussion, the coding scheme was refined and major misunderstandings about the interview comments and the interview context were clarified. For example, the interview comment "we all generally agree that it [CAD] is better because there is less of an opportunity for them [clients] to misunderstand what you are doing", which has the keyword "misunderstand" for Ambiguity, was initially coded by the independent coder to Expectation. After the clarification, the independent coder re-coded this comment to Ambiguity.

Interview Coding - Sample	Author	Independent Coder	Agreement
Category 1: Tools	48	48	1
Category 2: Tool-use Conditions	48	48	1
Category 3: Design Tool Characteristics	48	28	0.58
		Initial	2.58/3 = 0.86

Table 5.18 Reliability of Interview Coding (Initial)

However, there was still slight disagreement between the coders after the mediation. The final result of reliability regarding the DTCs was changed from 0.58 to 0.94. The disagreement also suggests that some DTCs are highly associated and difficult to distinguish from each other, which means it may require a certain level of expertise and specific context for the DTCs framework to be used effectively. All in all, the final reliability measurement of the interview coding is 0.98 (see Table 5.19).

Interview Coding - Sample	Author	Independent Coder	Agreement
Category 1: Tools	48	48	1
Category 2: Tool-use Conditions	48	48	1
Category 3: Design Tool Characteristics	48	45	0.94
		Final	2.94/3 = 0.98

Table 5.19 Reliability of Interview Coding (Final)

In terms of the interviews, a few limitations of the design and results of this experiment are noted. Although the data collected from each interview participant are reasonably rich (a minimum of 60 minutes for each interview) – which does provide a certain diversity regarding designers, designer's roles, design teams and design tools for generating reliable results – the sample size (12 participants) is relatively small.

The interviews aimed at providing an in-depth understanding of the patterns of use of Digital Sketching in practice; hence, the design of the interview study slightly sacrifices breadth of samples for the depth of data to fit in the project's time-frame. Ideally, a bigger sample size could further extend the results to be more universal. However, considering the study is conducted with design practitioners – and also comparing it with the sample sizes 2–10 in relevant studies with practising designers highlighted in Table 4.1 – the interview sample size of this study is considered reasonable.

Due to the time and environment restrictions, the diversity of the participating design firms (see Chapters 4 and 6) may not represent the full span of the diverse work environment in practice, especially in terms of location, culture and company size. The interviews were conducted in Australia and the origin of previous empirical observations is also primarily around Asia-Pacific areas. Expanding the diversity of the participating designers and design firms in the interviews may reflect some differences in the patterns of tool uses of different locations or cultures, which although not necessarily within the scope of this project, could be interesting for future studies. For example, larger design firms may have different working processes and different ways of assigning individual responsibilities. They might also have expanded external communication given an increased number of stakeholders. Companies that design for very specific products or industries might also have different design processes and approaches; e.g., consumer electronics, automotive and medical devices. However, the sample design consultancies in this study were chosen because their designers were exposed to a wider range of products and projects, and their design processes were more generic.

5.12 Targeted Groups of DTCs for Observation

In Chapter 4, an observation experiment is planned in the methodology in this study to triangulate the findings from interviews and deepen the understanding of research questions. The design of the observation experiment aims at providing in-depth insights on selected essential aspects of this study on Digital Sketching.

As suggested by the interview results, associations of DTCs may have some influences on each other, which could be critical for designers to acknowledge, select and use appropriate tools in different tool-use conditions. For example, the results suggest that the Flexibility offered by Digital Sketching in *externalisation* – namely, layers, copy and undo – may significantly contribute to the increasing of Level of Detail and the reduction of Use Cost for this tool. As such, understanding the associations of the key DTCs provides a more comprehensive understanding of how Digital Sketching manifests in practice (research question 2), and whether it could be a "pathway" to ease the transition between its neighbouring tools or not (research question 3). Due to the limited time of the project, four groups of associated DTCs were selected for further examination with an observation study based on their significance in the tool-use conditions. The results of the observation study are presented in Chapter 6. In Figure 5.23, four essential characteristics are highlighted in the centre of the diagram which could have a considerable impact on the patterns of the tool uses in *externalisation*, according to the interview data.

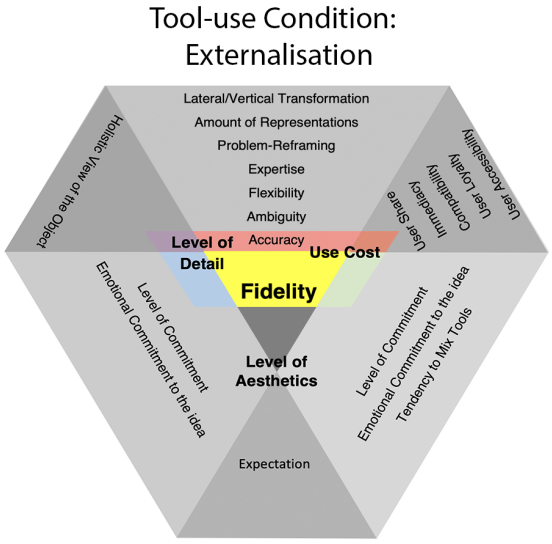


Fig. 5.23 Targeted Design Tool Characteristics in Externalisation for Observation

The first targeted association in this tool-use condition, to be further explored with the observation, is between Level of Detail and Use Cost. During the interviews, Use

Cost and Level of Detail were the two most referenced characteristics in *externalisation* (see Table 5.13). Participants also indicated that the Use Cost of a design visualisation tool is associated with the Level of Detail of the resulting design visualisation. Their association is chosen due to the importance of these two DTCs to the *externalisation*. The observation study aims to enrich the understanding of this association, which may help the tool users and the designers be able to regulate their Use Cost by being aware of the Level of Detail when externalising the design ideas.

Another selected association is between Fidelity and Accuracy. From the interview results, Fidelity is identified as the third most frequently mentioned of the DTCs among the three tools (see Table 5.13). Participants view the design tool-use activities in *externalisation* mainly as to "capture the idea that comes to your mind" (P9), and Fidelity is about how well the representation matches the designer's mental image. Therefore, Fidelity is selected to be further examined in the observation.

According to the interview results, Accuracy is essential as it is potentially connected to both Level of Detail and Use Cost as well as Fidelity (one-degree adjacent to them in Figure 5.23). Accuracy offered by the design tools is mentioned together with the most frequently mentioned DTCs in *externalisation*. Moreover, the interview results suggest a significant gap between the Accuracy of Traditional sketching and the Accuracy of CAD, which could cause the troublesome transitions in the Early-Middle phases in the design process. Therefore, the association between Accuracy and Fidelity is selected for further exploration with the observation.

To summarise, two groups of associations in *externalisation* are selected and targeted for the following observation study. They are targeted due to their potential high influences on the patterns of tool uses (research question 2). Specifically, they may also enrich the discussion of whether Digital Sketching could be a transitional tool to ease the transitions between its neighbouring tools or not (research question 3). This is because these targeted DTCs show noticeable bipolarised differences in Traditional Sketching and CAD. For example, if Digital Sketching turns out to offer more balanced associations of these targeted DTCs, it could be arguably useful to ease related troublesome transitions.

Similarly, two groups of associations are targeted for further observation in *external communication*. The decision-making reasoning of the selections is the same as above. Based on the interview results (Table 5.14), Level of Aesthetics and Use Cost are the two most frequently mentioned DTCs in this tool-use condition, which also have influences on each other. Hence, the association between Use Cost and Level of Aesthetics in *external communication* is targeted for observation.

The most interlinked characteristic in this tool-use condition is also selected as a target for observation; namely, Level of Detail. As is shown in Figure 5.24, Ambiguity is considered having associations with Level of Commitment and Level of Aesthetics as well as Level of Detail. This indicates that Ambiguity could play important roles in this tool-use condition. Besides, the levels of Ambiguity that Traditional Sketching and CAD can support are considered bipolar, while Digital Sketching may offer a moderate range of Ambiguity. As such, understanding the connections between Ambiguity and Level of Detail is also vital for exploring answers to both research questions 2 and 3.

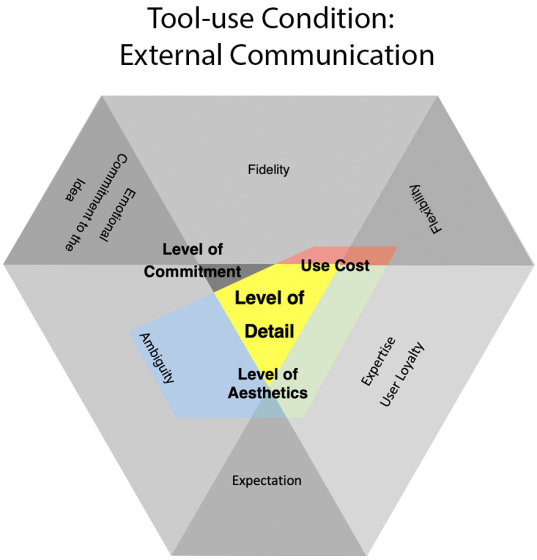


Fig. 5.24 Targeted Design Tool Characteristics in External Communication for Observation

No associations are selected in *internal communication* and *learning process* for further observation. This is partially due to the limited data on the *internal communication* from the interviews, which are not sufficient to make a choice of DTC associations to inspect. For the *learning process*, since the observation is designed to be unobtrusive to the designer's work conditions, it is not very feasible to catch the practising designers going through new learning experiences of certain tools; hence, observation targeting this use condition is undertaken. In total, based on the interview results, four groups of DTC associations are selected for the following observation study, as listed in Table 5.20.

Tool-use Conditions	Targeted Key Design Tool Characteristics
Externalisation	1. Level of Detail and Use Cost 2. Fidelity and Accuracy
External Communication	1. Level of Aesthetics and Use Cost 2. Level of Detail and Ambiguity

Table 5.20 Targeted Key Design Tool Characteristics for Observation

5.13 Chapter Summary

In this chapter, data from the interviews are analysed and key findings are presented, which opens up points for further observations and discussions in the following chapters.

To understand how Digital Sketching manifests in industrial design practice – namely, the patterns of its use and applications in industrial design practice – the interviews were coded based on a three-step coding scheme. A working model of tool-use conditions in industrial design is proposed for better analysing the interview data. Four conditions are nominated: *externalisation, external communication, internal communication* and the *learning process*. Comments from 12 practising designers from 3 different design firms are collected and grouped based on three categories: tools mentioned, related tool-use conditions of the comment, and the specific Design Tool Characteristics (DTCs) mentioned.

Sentiment analysis of the most frequently mentioned DTCs (the key DTCs) of Digital Sketching and the associations between them is conducted with respect to the four tool-use conditions. Results are presented and discussed early in this chapter for understanding the considerations and motivations behind the patterns of use of Digital Sketching in practice. Associations between the key DTCs of Digital Sketching are discovered, as they were frequently mentioned together by the participants when answering the same questions in the interviews. These associations of DTCs are considered important to give a multifaceted understanding of the manifestation of Digital Sketching.

Comparisons and reflections on the uses of its neighbouring tools, Traditional Sketching and CAD, are also given in this chapter. By drawing comparisons, the key DTCs in each tool-use condition among the three tools are given and the sentiment results of these DTCs in the three tools are discussed. In other words, with a focus on Digital Sketching, the differences and similarities of the three tools are more clearly shown with this step of the analysis, from which the comparative strengths of Digital Sketching can

be further discussed. It sets a basis to answer the research question 3, whether Digital Sketching could be a "pathway" to ease the transitions between its neighbouring tools or not. For example, the key DTCs of Digital Sketching in *external communication* seem to bridge the differences between Traditional Sketching and CAD. It explains the current mainstream use of Digital Sketching in practice as a beautifying tool for polishing traditional sketches for clients. This chapter presents the direct results of the interviews. Discussions of the answers to research questions are given in Chapter 7.

The comparisons between tools also support the existence of the associations between DTCs in different tool-use conditions across the three tools. Four groups of associations between key DTCs in *externalisation* and *external communication* are targeted for further exploration in the following observation experiment. This iteration from the interview results to observation is designed based on the methodology (see Chapter 4) to offer a more in-depth understanding of the patterns of use of design tools with relation to their characteristics; thereby, to give more comprehensive and reliable answers to research questions 2 and 3. Overall reliability of interview data is reviewed to ensure the credibility of results. Limitations of the interviews are also discussed in this chapter.

In conclusion, interview results indicate which combinations of DTCs motivate and concern designers regarding the selection and use of tools in various tool-use conditions. This forms a basis to understand the patterns of use of Digital Sketching during the Early-Middle design phases in practice. Said DTCs and the associations between them among the three tools also form a basis to explore the possibility of Digital Sketching being a "pathway" to ease the transitions between Traditional Sketching and CAD.

CHAPTER 6

OBSERVATION RESULTS AND ANALYSIS

The aim of conducting observation in this study is to provide richer insights on the manifestation of Digital Sketching, including its comparative strengths versus Traditional Sketching and CAD. Following the interviews, it is designed to explore how the three tools are used in practice, and its results are used in triangulating the interview results and supporting the discussion of research question 3. In Chapter 5, four groups of Design Tool Characteristics (DTCs) and the associations between them are targeted for observation. Based on the interview results, they seem to be essential to decoding what motivates and concerns designers to use Digital Sketching in the two primary tool-use conditions in practice: *externalisation* and *external communication*. In this chapter, these targeted DTCs across the three tools investigated are discussed first, then followed by the examination of the associations between the two DTCs in each group. As such, it helps form a multifaceted understanding of the manifestations of Digital Sketching and its neighbouring tool in the Early-Middle phases in industrial design practice. The results also deepen our understanding of how the key DTCs of Digital Sketching are associated with each other in different tool-use conditions and support further discussions on the manifestations of the tools.

6.1 The Procedure for Analysing the Observation

Based on the interview results, four groups of DTCs under two major tool-use conditions are targeted for the observation. In *externalisation*, the two groups are 1) Level of Detail and Use Cost, and 2) Fidelity and Accuracy. In *external communication*, the two groups are 1) Level of Aesthetics and Use Cost, and 2) Level of Detail and Ambiguity. As discussed in Section 5.12, these DTCs and the associations between them within one group could have essential influences on the use of Digital Sketching and potentially other designer visualisation tools in the Early-Middle phases in industrial design. No targeted DTCs were selected in *internal communication* and the *learning process*

for observation due to the focus of the overall project and the nature of the unobtrusive observation environment.

During four weeks, eight sessions of observation with four industrial designers (two sessions each designer) were conducted during the Early-Middle phases of their different design projects. The sessions were taken at the usual workplaces of the participants to capture more natural tool-use behaviours. As described in Chapter 4, each observation session took approximately 30 minutes, including 25 minutes of tool-use behaviour filming and a 5-minute semi-structured follow-up interview. As the observations aimed to gather the most natural tool-use experiences and behaviours, the designers had the freedom to choose the design tools, design objects and design phases based on their work schedule. Hence, before the start of each session, appointments were made with the designers via emails to make sure the observation content would fit the scope of the study; namely, using of any of the three tools investigated in the Early-Middle phases of the industrial design process. The follow-up interviews were also used to further clarify the tool-use conditions, purposes of the design activities, and the tool-use experience during the session.

The analysis of the observation focuses on decoding how the targeted DTCs affect each other across three different tools and whether Digital Sketching has advantages in offering better combinations of these associations. The analysis follows a three-step procedure summarised in Figure 6.1. The details are as follows.

Fig. 6.1 Analysis Procedure of the Observation Data

Stage 1. Processing Data

Due to the nature of commercial design projects, most of the content of the design representations collected in the observation sessions are confidential and thus images presented in this thesis are pixelated in places. A coding scheme is adopted to give a description of said content, where necessary examples from different projects are provided for illustrative purposes.

At this stage, the resulting representations shown in the observations are also categorised based on their type with the taxonomy of design representations by Evans et al.

(2010). It is the first step of decoding the observation materials to usable data. The results of this stage are described and presented in Subsection 6.3.1.

During the observation, two types of data were collected from the participants: the filming videos and the comments from the follow-up interviews. During this stage, comments on the tool-use experience from the follow-up interviews were also indexed to relevant DTCs to enrich the data.

Stage 2. Targeted DTCs and Associations

The collected videos offer rich data on both tool-use behaviours and resulting design representations. However, these commercial materials are mostly confidential. To be able to use these materials on analysing the levels of targeted DTCs offered by Digital Sketching and its neighbouring tools, a working coding scheme is provided based on the Design Tool Characteristics (DTCs) framework and the design representation taxonomy from Evans et al. (2010). Table 6.1 presents this coding scheme with what observation material and content were coded for each targeted characteristic.

Some of the DTCs are coded and measured by numbers of relevant elements; e.g., Level of Detail is measured by numbers of annotations/colours/tones. However, as a qualitative study, these resulting numbers in this coding step are only used as an indicator for forming the discussion rather than quantitative evidence of findings.

Targeted Key DTCs	Material Coded	Coding Type	Unit
Use Cost	Amount of Representations of the Design Object	Objective	Per session
Level of Detail	Colour/Tone/Engineering Annotation Numbers	Objective	Per Representation
Level of Aesthetics	Line-work Quality/Realism	Subjective	Final Representation
Accuracy	Dimensions/Mechanisms/Manufacturing	Mixed	Final Representation
Ambiguity	Number of Design Variations/Interview Comments	Mixed	Per session
Fidelity	Follow-up Interview Comments	Subjective	Per session

Table 6.1 Coding Scheme of the Observation Study

To be specific, during the observation analysis, the Use Cost of a design tool is assessed by the number of representations created in 25 minutes (one observation session) with the tool. This is because "time" is considered as the essential variable/factor by most of the interview participants and relevant studies (Bilda and Demirkan, 2003) for evaluating the Use Cost of a design visualisation tool.

Level of Detail is split into Aesthetic Detail and Engineering Detail for assessment in this study due to the different emphases of their roles during the Early-Middle phases in industrial design practice. Aesthetic Detail is assessed by the number of tones/colours involved with each representation. As Evans et al. (2010) state, the application of

colour/tone is used to enhance/support detail in design representations. Similarly, Engineering Detail is assessed by the number of engineering-related symbols, annotations, notes and marks on the resulting design representation at the end of a session. Both Aesthetic Detail and Engineering Detail are counted when evaluating the overall Level of Detail of the tool.

Level of Aesthetics is one of the targeted DTCs that are relatively subjective to assess. Expert judgement against the proposed aesthetic criteria (Hekkert and Van Wieringen, 1998) is used to evaluate the levels of aesthetics offered by the tools. The author, who has more than ten years' experience of studying and working in the industrial design field, is considered to have adequate epistemic and performative expertise (Weinstein, 1993) to make the judgement. The aesthetic criteria in this experiment are derived from the design tool taxonomy of Evans et al. (2010), which are line-work quality and realism of appearance. Figure 6.2(a) and 6.2(c) shows some examples as references for lower levels of line quality and less photo-realistic design representations. Similarly, Figure 6.2(b) and 6.2(d) give some examples of better line quality and more photo-realistic design representations.

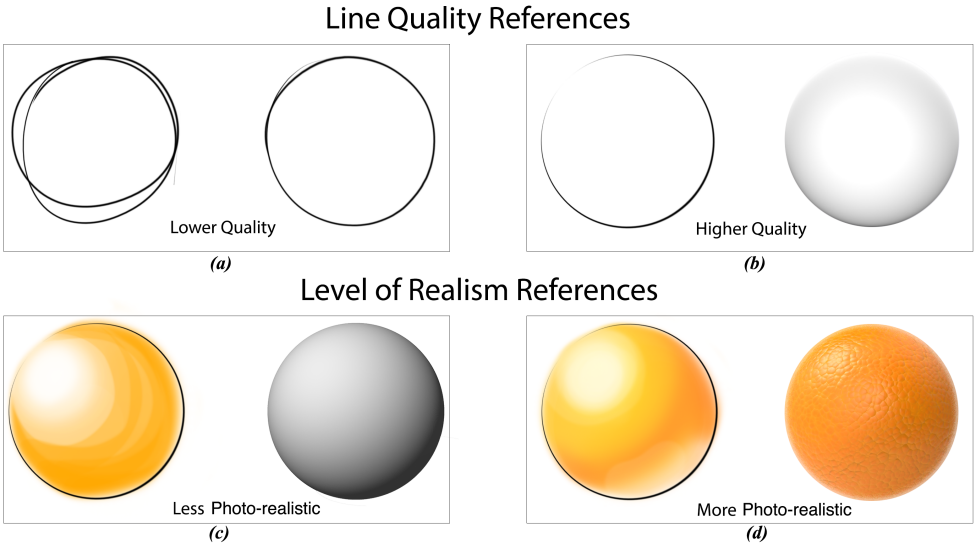


Fig. 6.2 References of Different Levels of Line Quality (a,b) and Realism (c,d) in Industrial Design Representations

Accuracy is assessed by dimensions/mechanisms/manufacturing (Evans et al., 2010) specifications on the design representations and supplementary information from the follow-up interview if applicable.

For Ambiguity, since highly ambiguous representation can usually stimulate more interpretations – thus potentially more design variations (Prats et al., 2009*b*) – it is assessed by the number of representations/design variations generated per session. Comments

from the follow-up interviews are also used to support the discussion where applicable.

Fidelity is mainly assessed by the comments from the follow-up interviews, as this characteristic is primarily about to what extent the representation matches the designer's mental image.

With the working coding scheme, the data from the observation study are mapped to each targeted characteristic at this stage. When the analysis on the individual characteristic is completed, the association between each pair is examined for a potentially clearer correlation to be further utilised.

Stage 3. Comparisons Across Three Tools

The last stage of the procedure is drawing comparisons of the targeted DTCs and their associations between the observed tools based on a synthesised understanding of the interview and observation results. This step is designed to discuss whether the levels of DTCs offered by Digital Sketching could be favourable or preferable or not for designers during the Early-Middle phases in the specific tool-use condition. Hence, the results may provide further support to argue the possibility of Digital Sketching being a transitional tool between Traditional Sketching and CAD for easing the troublesome transitions in practice.

6.2 Overview of the Observation Sessions

The observations are conducted within the scope of the Early-Middle phases of the industrial design process. Hence, all the results and discussions are within these phases unless noted explicitly. As shown in Chapter 4, among the four observation participants, two of them are considered as senior designers with more than five years of industry experience, and the other two are considered as junior designers. The distribution enables us to monitor the influences of Expertise on the targeted Design Tool Characteristics (DTCs) and ensure the results have a certain level of universality.

As the tools are chosen freely by the designers based on their projects, the selection of tools across the whole observation study may reflect some general tool-use tendencies in industrial design practice. Table 6.2 lists the tools observed in each session, and session 1 and session 2 are referenced as S1 and S2 hereafter.

Participant	Experiences	Tool(s) Session 1 (S1)	Tool(s) Session 2 (S2)
Ob1	5-10 years	Traditional Sketching	Traditional Sketching
Ob2	1-4 years	Digital Sketching	Traditional and Digital Sketching
Ob3	1-4 years	Traditional Sketching	CAD and Traditional Sketching
Ob4	5-10 years	CAD and Traditional Sketching	CAD and Traditional Sketching

Table 6.2 Design Tools Observed in the Observation Sessions

To be specific, four designers used Traditional Sketching at some point during their sessions, and two of them have used CAD together with Traditional Sketching. A tendency to mix the use of Digital Sketching and CAD with Traditional Sketching was noted in the observation sessions. The participating designers are likely comfortable with mix-using design tools on different platforms and media. One out of four participants chose to use Digital Sketching during observations. This result aligns with the motivation of this study, which is the limited use of Digital Sketching in industrial design practice. The limitation is caused by data on Digital Sketching from the observation study being relatively small compared to Traditional Sketching and CAD. Nevertheless, said participant had extensive experience using Digital Sketching professionally; hence, the tool-use behaviours and patterns observed are deemed representative. Equally observing the designers using neighbouring tools can also provide data that explains the relative underuse of Digital Sketching.

6.3 Observation Results

In this section, the observation results are presented as well as an initial discussion of them. Further discussion of the observation results, the basis to answering research question 3, is given in Chapter 7. The results in this chapter are described in terms of the targeted DTCs (and their associations) offered by the observed tools. The design tools and representations, tool-use behaviours, and comments from the follow-up interviews are analysed first. Then the comparisons between Digital Sketching and its neighbouring tools are drawn based on observation data, interview results and literature support. The understanding of these essential DTCs in the two primary tool-use conditions, and how they are interlinked and associated with each other, could deepen our understanding of the manifestation of Digital Sketching. Comparing results between the three tools forms a more solid basis to answer research question 3, whether Digital Sketching can be a pathway or not based on its comparative strengths. The detailed analysis procedure was given in Section 6.1 and Figure 6.1. The observation results and the initial discussion are as follows.

6.3.1 Types of Design Representations in the Observation

Four participants generated different design representations using various combinations of Traditional Sketching, Digital Sketching and CAD modelling tools. To make the confidential design representations usable for the analysis, they were first categorised based on a taxonomy of design representations from Evans et al. (2010), which is a well-accepted design representation taxonomy that is suggested by the Industrial Designers Society of America (IDSA), and highly cited in industrial design literature.

The design phases where the design activities happened and the tool-use conditions of each observation session are determined from both the pre-appointment email with the participant and the comments of the 5-minute follow-up interview. With the clarified design phases and tool-use conditions, the design representations are identified according to the descriptions on the iD cards from Evans et al. (2010), and the results are given in Table 6.3. Note that the *Concept Model* in the table is not listed on the iD card, which is an observed pattern of use of CAD in the Early-Middle phases in industrial design practice. It is defined in this study as the use of 3D CAD software simulating and exploring the appearance of potential design solutions in the Early-Middle phases of the industrial design process (similar to the Concept or Development stages defined on the iD cards).

Session	Tool(s)	Tool-Use Condition	Design Phase	Representation Type
Ob1 S1	Traditional Sketching	External Communication	Early	Study Sketch
Ob1 S2	Traditional Sketching	Externalisation	Middle	Perspective Sketch
Ob2 S1	Digital Sketching	External Communication	Middle	Sketch Rendering
Ob2 S2	CAD Digital Sketching	External Communication	Middle	Concept Model Information Sketch
Ob3 S1	Traditional Sketching	Externalisation	Early	Idea Sketch
Ob3 S2	CAD Traditional Sketching	Externalisation	Early	Concept Model Study Sketch
Ob4 S1	CAD Traditional Sketching	Externalisation	Middle	Design Development Model (CAD Version) Information Sketch
Ob4 S2	CAD Traditional Sketching	Externalisation	Early	Concept Model Memory Sketch

Table 6.3 Types of Design Representations in the Observation

The coding process of the design representation from observation participant 1 (hereafter Ob1) in observation session 1 (hereafter S1) is given as an example. The design phase of S1 from Ob1 is confirmed by the participant as the early phase and the resulting design representation are traditional sketches, which help us narrow down the options on the iD cards. Evans et al. (2010) state that "Study Sketch is used to investigate appearance, proportion and scale in greater detail than Idea Sketch. Often supported by the loose application of tone/colour", which frequently happens in the early "Concept"

design stage. Ob1 claims that the design representation generated is used to "ideate for aesthetics, form and concepts for a neat update" with the client; thus, it matches the description of the "Study Sketch". From the design representation itself, loose application of tone/colour is noticed. By matching these variables, the representation type from S1 of Ob1 is determined.

The rest of the design representations generated from the observation sessions are categorised in a similar way. In Appendix D, the types of design representations in the observations are provided with visual references from iD cards by the Industrial Designers Society of America (IDSA). The visual reference for Concept Model in the appendix is selected from the design samples of a CAD software Fusion 360 online gallery (Autodesk, 2020), based on its similarity to the representations observed in the study.

6.3.2 Level of Detail and Use Cost in Externalisation

As discovered in the interview results, the Use Cost of design visualisation tools is critical in *externalisation*, especially during the Early-Middle phases of the industrial design process. From observation, the Level of Detail (actual and expected) of the resulting representations seems to have an impact on the Use Cost of the selected tool. The association between Level of Detail and Use Cost appears reasonable since it is obvious that designers need to spend more time on visualising more detailed design representations. However, the correlation gradient of this association could vary from tool to tool. In other words, the increase in Use Cost for a similar increase in Level of Detail among design visualisation tools can differ.

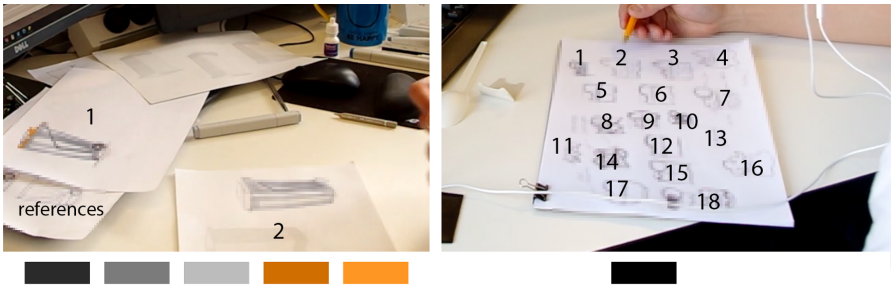
Moreover, if the mainstream use of the tool is creating highly detailed representations, it may also influence other designers' perception of Use Cost for this tool. Therefore, an investigation of this association across Traditional Sketching, Digital sketching and CAD is important for a more comprehensive understanding of the use of Digital Sketching in *externalisation*.

The association between Level of Detail and Use Cost is observed in the use of Traditional Sketching and CAD in *externalisation*. Data from three participants across five observation sessions (Ob1-S2, Ob3-S1/-S2, and Ob4-S1/-S2) are used to further examine the two DTCs and the associations. The raw data is given in Table 6.4 for reference.

Session	Tool(s)	Phase	Representation Type	Number of Representations	Aesthetic Detail	Engineering Detail
Ob1-S2	Traditional Sketching	Middle	Perspective Sketch	5 sketches	Linework	3 Ruler Guided Cross-sections
Ob3-S1	Traditional Sketching	Early	Idea Sketch	18 sketches	Linework	No Notes
Ob3-S2	CAD Traditional Sketching	Early	Concept Model Study Sketch	9 sketches	Linework	No Notes Visually Checked With CAD
Ob4-S1	CAD Traditional Sketching	Middle	Development Model Information Sketch	2 sketches	Marker Rendered	No Notes Checked With Printed CAD
Ob4-S2	CAD Traditional Sketching	Early	Concept Model Memory Sketch	Less than 1 model	Real-time Rendered	Marked With Numeric Dimensions

Table 6.4 Externalisation: Use Cost and Level of Detail in Observation Data

According to the observation data, the number of traditional sketches created within one observation session (25 minutes) varies from 2 to 18, which seems to correlate with the resulting Level of Detail. In Figure 6.3, the two border examples of the range of Traditional Sketching are given as a reference. The sketches from Ob4-S1 (2 sketches) in Figure 6.3(a) and Ob3-S1 (18 sketches) in Figure 6.3(b) are relatively simple as the projects were both in the early phase. They also have a similar level of Engineering Detail in terms of numbers of functioning features, engineering annotations, or any intentions of developing functioning features. Since Ob3 and Ob4 have similar years of working experience – hence, we can assume they have similar expertise – why did participant 4 (Ob4) take more time to visualise these sketches?



***(a)* Ob4-S1** ***(b)* Ob3-S1**

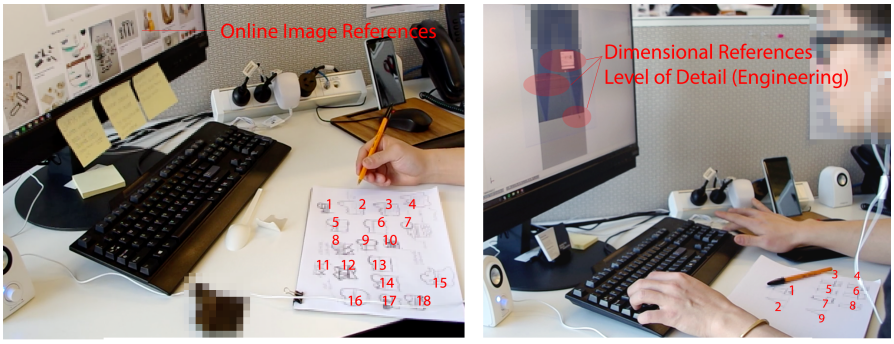
Fig. 6.3 Level of Detail and Use Cost of Traditional Sketching in Externalisation

The levels of Aesthetic Detail of these sketches show significant differences between Ob3-S1 and Ob4-S1. In Figure 6.3, the levels of Aesthetics Detail are compared between these two sessions based on the analysis of the colour tones/values. It seems the Use Cost of each representation could vary depending on the resulting level of Aesthetic Detail. According to the observation results, the traditional sketches with a high Level of Detail could take half a session to visualise, while the ones with a low Level of Detail could be done in less than a few minutes each.

The association between the Level of Detail (Engineering) and Use Cost in *externalisation* is also supported by the observation data, but their correlation is more obvious in CAD or the mixed-use of CAD and Traditional Sketching. Observation data suggest

that when creating design representations with a similar Level of Detail (Aesthetics), the increase of Engineering Detail could also lead to a potential increase of Use Cost of a design visualisation tool.

Figure 6.4 displays the final representations from Ob3-S1 and Ob3-S2, where both are single-coloured, linework-only traditional sketches. However, the Study Sketches from Ob3-S2 in Figure 6.4(b) are visually guided by a CAD Concept Model that has a high Engineering Detail on dimensions. The total numbers of traditional sketches created by participant 3 (Ob3) in S1, as is shown in Figure 6.4(a), is double that of traditional sketches in S2 as is shown in Figure 6.4(b). In other words, the Use Cost of each design representation with a higher level of Engineering Detail in S2 doubled the Use Cost of the one with a lower level of Engineering Detail in S1. Similarly, the correlation can be seen with different participants. As shown in Table 6.4, Ob1 created five traditional sketches in Ob1-S2, which are also linework-only sketches, but included three cross-section sketches guided and measured with rulers. This number is lower compared to Ob3-S1 and Ob3-S2, but the resulting representations are considered Perspective Sketches displaying a high level of Engineering Detail. In other words, when the Engineering Detail of Traditional Sketching increases in this tool-use condition, the Use Cost also increases.



(a) **Ob3-S1** *(b)* **Ob3-S2**

Fig. 6.4 Level of Detail (Engineering) and Use Cost in Externalisation

To summarise, the Level of Detail of Traditional Sketching in the observation sessions is generally low with low Use Cost. Hence, both interview and observation data suggest that the Use Cost of Traditional Sketching is generally low concerning the extent of lateral transformation occurring. However, the Use Cost could increase when the Level of Detail increases. The association between Level of Detail and Use Cost in Traditional Sketching is considered to have a positive correlation in the Early-Middle phases of the industrial design process in practice.

In CAD, Level of Detail and Use Cost in *externalisation* are observed as higher than

Traditional Sketching, but a similar correlation between these two DTCs is indicated. For example, Figure 6.5 demonstrates the progress of participant 4 (Ob4), working on the Level of Detail (Engineering), of a product during his second session (Ob4-S2). The Use Cost is considerably high as the participant spent 25 minutes on adding and detailing one feature of the product as is shown in Figure 6.5(a) to Figure 6.5(c). The Level of Detail also significantly increased at the end observation in terms of more dimensional references and more accurate inner structure as is shown in Figure 6.5(b). Hence the high Use Cost and high Level of Detail are frequently observed in industrial design practice.

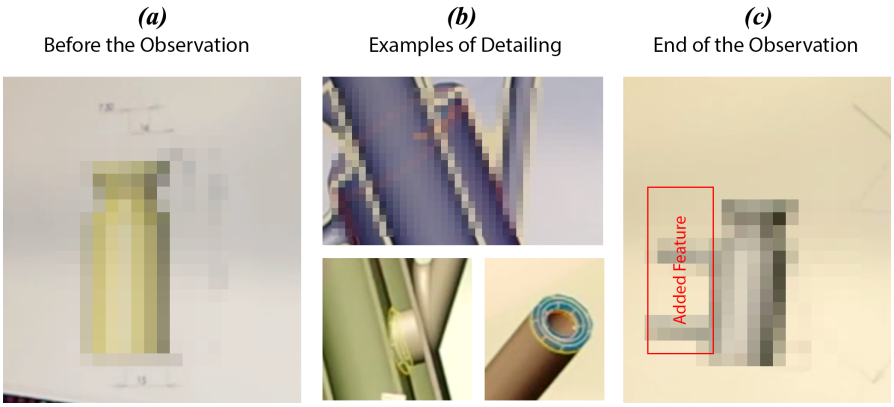


Fig. 6.5 Developing the Level of Detail (Engineering) in CAD in Externalisation

In terms of the correlation of the association between Use Cost and Level of Detail in CAD, the premise that the low Level of Detail also requires less time to build is argued with comments from participant 3 (Ob3). In the follow-up interview, Ob3 mentioned that the "block" CAD model used in Ob3-S2 for guiding the traditional sketches is "not a perfect model" with basic dimensional references; that is, a CAD model with low Level of Detail. According to Ob3, the model was done "quickly" with low Use Cost. In other words, the observation results suggest that the correlation between Level of Detail and Use Cost of CAD could also be positive.

This association may help to explain why not only CAD but also Digital Sketching are considered as having high Use Cost in *externalisation* in the interview results. As no use of Digital Sketching in this tool-use condition is observed in the study, the following discussion of Digital Sketching is primarily relying on the interview results and empirical observations of the author in industry and education. Comparisons between Digital Sketching and observed Traditional Sketching and CAD are proposed for further debate in the future.

According to the interview results, the stereotypical impression of Digital Sketching is that it is a tool to create more refined and detailed representations. In other words,

it is generally expected to create representations with a higher Level of Detail than Traditional Sketching. As observation data suggests, a high Level of Detail is likely associated with a high Use Cost in this tool-use condition, which could form a significant disadvantage of Digital Sketching that may lead to its lower usage in *externalisation*. On the one hand, a high Level of Detail is expected from digital sketches in general. On the other hand, Digital Sketching also makes it easier for designers to focus on achieving finer details by offering advanced features and control.

However, the observation data indicates that Digital Sketching could remain at low Use Cost if used for creating low Level of Detail. Even if the use of Digital Sketching in Ob2-S2 is in *external communication*, the techniques for low Level of Detail and low Use Cost, and the comments on the use of Digital Sketching, could still be applicable for other tool-use conditions. For example, participant 2 (Ob2) demonstrated a few techniques of using Digital Sketching with low Level of Detail, namely "colour blocks" and "silhouette", which are helpful to "develop the graphic for the form" and do "speed form sketching". Ob2 also commented that the "copy and paste" features are very efficient to "mashing things together" for ideating in the Early-Middle design phases. This finding also indicates that the features of Digital Sketching inherited from the digital media/platform could be helpful in terms of lowering down its Use Cost. Arguably, the Use Cost could vary from low to high depending on the resulting Level of Detail.

The observation results suggest that Use Cost and Level of Detail in *externalisation* seem to have positive correlations with each other across the three tools investigated in the Early-Middle phases. As a summary, Table 6.5 shows the proposed levels of DTCs and the associations based on interview and observation data for further discussion. It indicates that Digital Sketching could maintain low Use Cost when used for creating low Level of Detail as well as CAD (block CAD). Hence, this association shows the use of Digital Sketching in this tool-use condition could be reconsidered. The awareness of the association between Use Cost and Level of Detail in *externalisation* may change the stereotypical impression of Digital Sketching being a high Use Cost tool and inspire more creative use of Digital Sketching in practice based on its characteristics.

Tool-use Condition: Externalisation		
DTCs / Tools	Use Cost	Level of Detail
Traditional Sketching	Generally Low	Generally Low
Digital Sketching	Low-High	Low-High
CAD Modelling	Medium-High	Low-High

Table 6.5 Proposed Association Between Use Cost and Level of Detail Across the Three Tools in Externalisation Based on Interview and Observation Data

6.3.3 Accuracy and Fidelity in Externalisation

Another association in *externalisation* to be examined with observations is Accuracy and Fidelity. During the observations, designers showed mixed-use of Traditional Sketching with CAD models to handle the Accuracy of the design concepts in the Early-Middle phases regarding the dimensions and mechanisms. This pattern of use is also mentioned by many interview participants. The raw data examined is given in Table 6.6. The observations and follow-up interviews help to reveal the interrelated benefits and shortcomings of Accuracy and Fidelity in this tool-use condition across the three tools.

Session	Tool(s)	Phase	Representation Type	Designer's Comment towards Fidelity	Accuracy
Ob1 S2	Traditional Sketching	Middle	Perspective Sketch	Not quite sure where everything to be placed yet.	Hand Measured With Rulers
Ob3 S1	Traditional Sketching	Early	Idea Sketch	Refine the idea before CAD.	Freehand
Ob3 S2	CAD Traditional Sketching	Early	Concept Model Study Sketch	Sketch the proportions then translate into CAD.	Freehand Visually Guided by CAD
Ob4 S1	CAD Traditional Sketching	Middle	Development Model Information Sketch	Need to figure out the system before going into CAD.	Freehand Guided by Printed CAD
Ob4 S2	CAD Traditional Sketching	Early	Concept Model Memory Sketch	Taking notes for information.	Numeric Inputs Precise CAD

Table 6.6 Externalisation: Fidelity and Accuracy in Observation Data

In Figure 6.6, observation participant 1 (Ob1) demonstrated the use of Traditional Sketching to ideate solutions for a project with relatively more technical details.

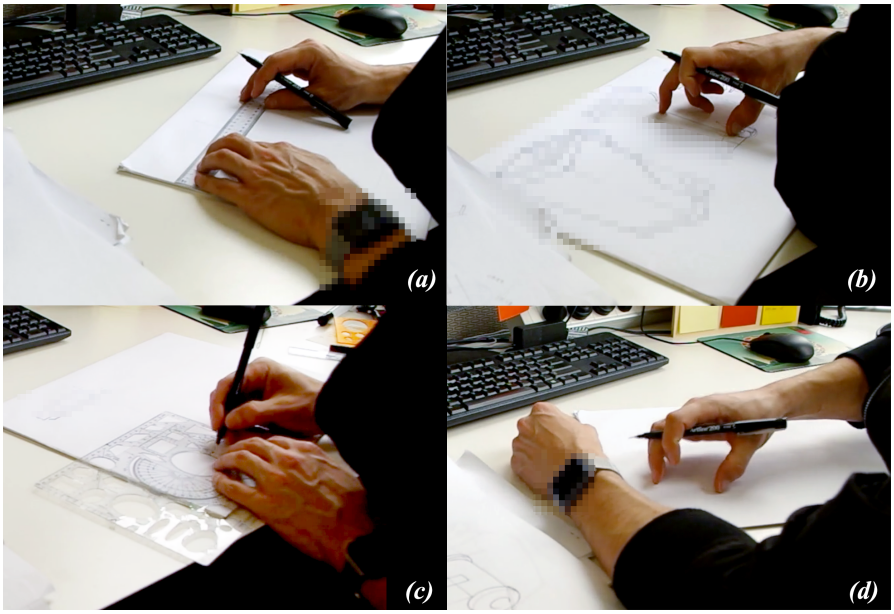


Fig. 6.6 Use of Traditional Sketching in Externalisation

Examples in Figure 6.6(a) and Figure 6.6(c) show the participant use different types of rulers to guide the Accuracy of the representation. Similarly, as seen in Figure 6.6(b)

and Figure 6.6(d), the participant also often use hands to run rough measurement of the design representation. The examples indicate that using Traditional Sketching to create higher levels of Accuracy on design representations can be challenging. At the same time, the resulting Accuracy may not be ideal. However, designers also mentioned in their follow-up interviews that Traditional Sketching does not require a clear mental image of the product to start with, which has an advantage in the Early-Middle design phases. In other words, observations concur that Traditional Sketching was usually used to generate less accurate design sketches that also did not require high Fidelity to start.

According to the interview results, designers can start working with pen and paper on a rough idea, and they feel free to move from idea to idea. In the observations, observation participant 1 (Ob1) stated after the Ob1-S1 that "I chose to use Traditional Sketching because we are not quite sure where everything to be placed yet". Traditional Sketching may also save designers' time on fixing mistakes, and hence could lower the Use Cost by reducing sunk cost, which is crucial in the early design phase. For example, Ob1 also commented on a mistake he made with Traditional Sketching during the observation sessions: "The same mistake in CAD will take a lot longer to fix." In other words, the Use Cost of Traditional Sketching may be considered a lot lower than CAD by designers in the Early-Middle phases. However, Traditional Sketching fails to offer high Accuracy for dimensions, and the design representations generated could be out of scale or proportion. It may require additional iterations in CAD later in the design process to obtain the desired Accuracy .

During the observations, designers showed mixed-use of CAD and Traditional Sketching to balance Accuracy and Fidelity in *externalisation*. According to the interview results, using CAD for figuring out dimensions for the mechanisms within a design is common among designers. They can accurately represent designs with dimensions and thus evaluate the design concepts in the right scale. Designers also mentioned that CAD simplifies resizing of the product or components.

However, CAD also requires clearer mental images to work with, but designers do not always have a high Fidelity mental image of a design in early *externalisation*. As both Ob1 and Ob3 mentioned after their observation sessions, CAD requires "more research to figure out the [product] system", and they need to "refine the function of the idea and the aesthetics before CAD". For example, Ob4 using a printed CAD created in Figure 6.7(a) as an underlay to guide the dimensions of the traditional sketches in Figure 6.7(b) during *externalisation*. This technique was regarded by the participant as a common practice in this tool-use condition and was observed across 3 sessions.

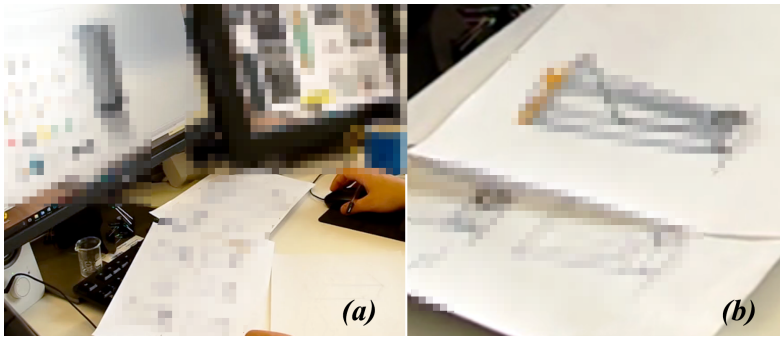


Fig. 6.7 Use of CAD as Underlays for Traditional Sketching in Externalisation

Combining Traditional Sketching and CAD would appear to reduce the requirement of high Fidelity of CAD in *externalisation*; however, it could also cause redundant work later on due to Accuracy, as the Accuracy of Traditional Sketching is low by nature. For example, Ob3 stated that "the proportions still need to 'translate' into CAD" after Traditional Sketching. Similarly, Ob4 mentioned that annotations and notes on traditional sketches are essential for getting precise CAD later in the industrial design process. The interview participants also admitted that "sometimes it [the design concept] seems fine on paper, but once you put it into CAD, it doesn't fit." In other words, the low Accuracy in Traditional Sketching can cause errors or mistakes in terms of scale, proportion or jointing in later design phases when the requirement of Accuracy becomes higher.

This observation concurs with the interview results in that the relative low Accuracy in Traditional Sketching, which transitions directly into CAD, can cause additional iterations in the transitions to CAD. However, the low Accuracy and requirement of Fidelity in Traditional Sketching may require less mental preparation to use and cause less "sunk cost" to make changes that could ultimately lead to lower Use Cost. At the same time, the high Accuracy of CAD seems to require high Fidelity that may lead to high Use Cost, which is not necessarily preferable in the Early-Middle design phases in practice. Since high Accuracy has its benefits in design outcomes, the balance of the requirements of Accuracy and Fidelity could be a real struggle, especially in the Early-Middle design phases. A more balanced mixed-use of CAD and Traditional Sketching has been observed as an attempt from the designers to tackle this issue. Nevertheless, this association between Accuracy and Fidelity suggests an opportunity to explore the use of Digital Sketching in *externalisation* for a more effective solution to the problem.

Using Digital Sketching to approach this Accuracy-Fidelity issue in this tool-use condition could potentially lead to effective outcomes and low Use Cost. In Ob2-S2, participant 2 (Ob2) demonstrated the mixed-use of Digital Sketching with CAD models in externalisation in the middle phase of a design project. The results indicate that Digital Sketching could offer a moderate combination of these two DTCs for achieving more

effective design representations.

As an affordance inherited from digital media, Digital Sketching allows numerical inputs for achieving higher Accuracy. For example, many Digital Sketching software products have features for inputting and displaying accurate dimensions of the sketches created; e.g., shape tools and grids in Adobe Illustrator. Also, for instance, Ob2 used numeric input in Digital Sketching to create an accurate representation of a furniture product. According to the observation results, the switch between Digital Sketching and CAD seems to be smoother than the switch between Traditional Sketching and CAD. This is evidenced in skipping the steps of printing and scanning, as well as the narrower gap in levels of accuracy between Digital Sketching and CAD.

To be specific, Ob2 in Ob2-S2 mentioned that "since there are dimension requirements from the brief, I will do it in Photoshop [a Digital Sketching software product] and make everything in scale from the beginning". Similar to CAD, Digital Sketching offers easy operations of Accuracy so that designers can rescale, test and determine the right dimensions of the design concepts. When ideating for mechanisms and arrangements of the design, Digital Sketching could maintain a low requirement of Fidelity compared to CAD. Thus, it could be similar to Traditional Sketching but with a higher Accuracy. For instance, in Digital Sketching, a simple curve with accurate dimensional references can represent a specific type of spring as a placeholder for further ideation of the component arrangement. It could take longer and a few more steps to build this spring in CAD due to the higher Fidelity of CAD representations, which would not be necessary for early *externalisation*. Similarly, to sketch the same spring in Traditional Sketching could be less accurate, or may take longer to achieve the desired Accuracy.

As is summarised in Table 6.7, Accuracy and required Fidelity of the tools seem to have a positive correlation. The increase in Accuracy of the design representations may increase the required Fidelity to work with the tools. According to the interview and observation results, Digital Sketching offers a broad and intermediate range of Accuracy and Fidelity, which in turn presents a more balanced combination of these characteristics. In other words, the association between Accuracy and required Fidelity in Digital Sketching tends to have a moderate nature, which could be further utilised by the designers in *externalisation* during the Early-Middle design phases.

Tool-use Condition: Externalisation		
DTCs / Tools	Accuracy	Requirement of Fidelity
Traditional Sketching	Generally Low	Generally Low
Digital Sketching	Medium-High	Low-High
CAD Modelling	Generally High	Generally High

Table 6.7 Proposed Association Between Accuracy and Required Fidelity Across the Three Tools in Externalisation Based on Interview and Observation Data

6.3.4 Level of Aesthetics and Use Cost in External Communication

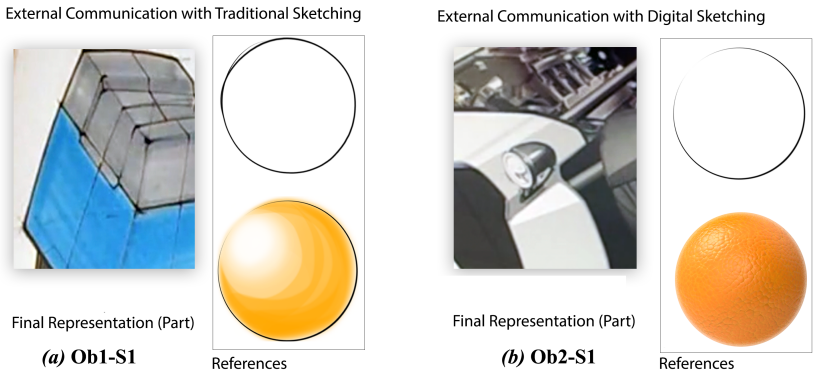
In the interviews, designers paid a lot of attention to the Level of Aesthetics and Use Cost (and the associations between them) in *external communication*. From both interview and observation data, Digital Sketching seems to offer a useful combination of these two DTCs for designers to utilise in this tool-use condition. To be specific, Digital Sketching shows the capability of achieving a higher Level of Aesthetics than both Traditional Sketching and CAD for less time spent in most design scenarios. The use of Traditional Sketching and Digital Sketching in this tool-use condition was observed, and the raw data is given in Table 6.8.

Session	Tool(s)	Phase	Representation Type	Number of Representations	Realism	Line Quality
Ob1 S1	Traditional Sketching	Early	Study Sketch	3 sketches	Low-Medium	Fuzzy Ends
Ob2 S1	Digital Sketching	Middle	Sketch Rendering	Less than 1 sketch	High	Clean
Ob2 S2	CAD Digital Sketching	Middle	Concept Model Information Sketch	1 sketch	Medium-High	Clean

Table 6.8 External Communication: Use Cost and Level of Aesthetics in Observation Data

Participant 1 (Ob1) was using Traditional Sketching in Ob1-S1 to create design representations for external clients and other non-designer stakeholders in the early phase. As a result, simple marker-rendered Study Sketch and two supplementary Study Sketches were generated within one session (25 minutes). Participant 2 (Ob2) was using Digital Sketching in Ob2-S1 in the middle design phase for *external communication*, and only two components of the product were further polished with Sketch Rendering after one session. In Ob2-S2, the participant used Digital Sketching to trace over the CAD model, and the one resulting digital sketch was to be used in the product manual for clients. This suggests that the Use Cost of Digital Sketching is potentially higher than Traditional Sketching since more representations were generated with Traditional Sketching in one session.

However, the observation data suggest that the Level of Aesthetics of the resulting digital sketch from Ob2-S1 in Figure 6.8(b) is a lot higher than the most polished traditional sketch from Ob1-S1 in Figure 6.8(a). A representative corner of these design representations was cropped and displayed in Figure 6.8 to protect commercial confidentiality, from which the resulting line quality and level of realism on the digital sketch are seen higher than the traditional sketch. The judgement was made based on the author's expertise and also checked with an independent expert for reliability (see Section 6.4 for further information).



(a) **Ob1-S1** *(b)* **Ob2-S1**

Fig. 6.8 Level of Aesthetics of the Representations in External Communication from the Observations

The Use Cost of generating the lower Level of Aesthetics in the traditional Study Sketch is significantly lower than the higher Level of Aesthetics in the digital Sketch Rendering. The association between Use Cost and Level of Aesthetics in *external communication* is observed with the use of both Traditional Sketching and Digital Sketching. For CAD, the discussion is mostly drawn from the *review-based descriptive study I* and the interview results.

This observation suggests the Use Cost of a design tool could be proportionally correlated to the Level of Aesthetics on the design representations in *external communication*. In other words, the high Use Cost of Digital Sketching could be related to the stereotyped use of it in this tool-use condition for generating highly polished digital sketches. However, it is contended that the high Use Cost of Digital Sketching is not necessarily a fixed cost and could be regulated or lowered. From both the interviews and observations, it is well accepted to use Digital Sketching to make "neater" and "cleaner" polished versions of the ideas that were previously created on paper. For instance, participant 2 (Ob2) commented that he creates digital sketches from previous traditional sketches before meeting with clients (and other non-designer stakeholders) because of the style and the "feel" offered by Digital Sketching.

The study shows that sometimes the Level of Aesthetics of Digital Sketching could

be considered even higher than CAD renderings in the Early-Middle design phases because of its "more expressive sketching style". Even though the observation participants consider CAD renderings as the most aesthetic representations in this tool-use condition in general, the Use Cost of it for achieving a similar Level of Aesthetics could be higher compared to Digital Sketching. Participant 1 (Ob1) stated that "CAD is for the more formal presentation to the client", which is "professional", but Digital Sketching "can be done relatively quickly". Arguably, in the Early-Middle phases, Digital Sketching may offer a suitable Level of Aesthetics with relatively less Use Cost compared to CAD.

All in all, the levels of these two DTCs in the three tools in this study are summarised for discussion in Table 6.9. The interview and observation results indicate that Digital Sketching can offer a wide range of Level of Aesthetics with associated low to moderate Use Cost in *external communication*, which can be beneficial for designers.

Tool-use Condition: External Communication		
DTCs / Design Tools	Level of Aesthetics	Use Cost
Traditional Sketching	Low-Medium	Generally Low
Digital Sketching	Low-High	Low-Moderate
CAD Modelling and Rendering	Generally High	Generally High

Table 6.9 Proposed Association Between Level of Aesthetics and Use Cost Across the Three Tools in External Communication Based on Interview and Observation Data

6.3.5 Level of Detail and Ambiguity in External Communication

From the interviews, designers show more positive sentiments towards the Ambiguity of Digital Sketching in *external communication* than both Traditional Sketching and CAD, which could be related to its Level of Detail. The observation data concurs with the association between the Level of Detail and Ambiguity in this tool-use condition during the Early-Middle phases. The raw data is given in Table 6.10.

Session	Tool(s)	Phase	Representation Type	Number of Variations	Aesthetic Detail	Engineering Detail
Ob1 S1	Traditional Sketching	Early	Study Sketch	2	Marker Rendered (1 view) Linework (mostly)	Not specified
Ob2 S1	Digital Sketching	Middle	Sketch Rendering	None	Highly Polished Digital Rendered	Not Specified
Ob2 S2	CAD Digital Sketching	Middle	Concept Model Information Sketch	None	Digital Linework	Build upon CAD

Table 6.10 External Communication: Ambiguity and Level of Detail in Observation Data

In Figure 6.9, the Level of Detail (Aesthetic) of the example representations created in Ob1-S1 and Ob2-S1 is illustrated by displaying the used colour values. The example in Figure 6.9(b) shows that Digital Sketching can be used in practice for generating a higher level of Aesthetic Detail than Traditional Sketching. In terms of Engineering Detail, there are no engineering-related annotations, notes or technical drawings seen in either traditional sketch or digital sketch from the particular observation sessions (Ob1-S1 and Ob2-S1). As a result, during the observation sessions, more design variations were generated with Traditional Sketching with a lower level of Aesthetics Detail compared to Digital Sketching.

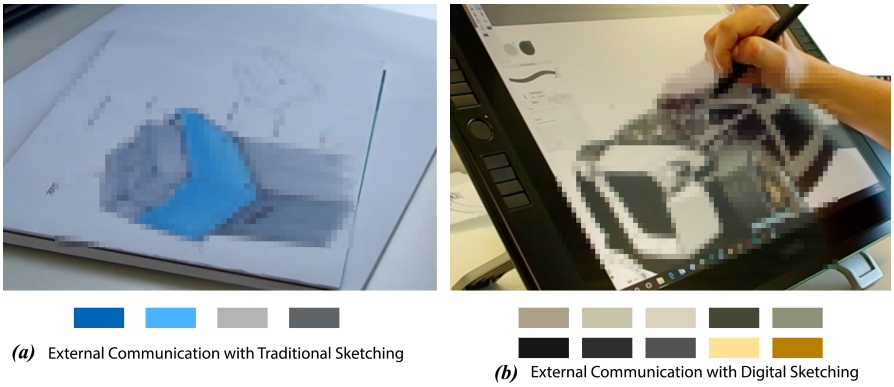


Fig. 6.9 Level of Detail (Aesthetic) of the Representations in External Communication From the Observations

Comparing the resulting sketches between Ob1-S1 and Ob2-S2, the levels of Aesthetic Detail between the traditional sketches and the digital sketch are similar. However, the level of Engineering Detail of the digital sketch from Ob2-S2 can be considered higher because it is built upon a CAD rendering with proportional, dimensional and other technical restrictions. According to the observation results, the number of design variations with Traditional Sketching is higher than with Digital Sketching in a 25-minute session. Hence, in *external communication*, the observation data show that the correlation of the association between Ambiguity and Level of Detail could be negative. In other words, the more detailed a design representation is, the more likely it can be interpreted as the same among different audiences, which is also in line with our common sense.

Ambiguity is noted as one essential characteristic in this tool-use condition. From the designers' perspective, Ambiguity in this tool-use condition is examined by how many design alternatives are generated within a session. It is essential during the Early-Middle phases to generate design alternatives or transformations, but the favourable levels of Ambiguity differ from *external communication* to *externalisation*. In terms of Traditional Sketching, Ob1 created two design variations, which suggests that Tra-

ditional Sketching offered a relatively high level of Ambiguity to facilitate the design transformations. Ob2 did not create any variations in the sessions but generated more details with Digital Sketching. This is an example where Digital Sketching offers lower Ambiguity and hence fewer design transformations compared to Traditional Sketching.

However, according to the study results, whether the Ambiguity of a design tool is favourable in *external communication* or not depends more on how it affects non-designer stakeholders' interpretations of the design. From the follow-up interviews, the observations concur with the interview results that designers believe the levels of Ambiguity of Traditional Sketching are generally too high for non-designers to get the design idea in this tool-use condition. At the same time, CAD could be too fixed in the Early-Middle phases. For example, even Ob1 stated after the observation session that "these sketches [pointing at the traditional sketches created in the session] need a bit of brain to understand". Similarly, Ob1 commented on CAD models in *external communication* that CAD is introduced to the clients as a sign that the design is "finalised". Arguably, neither Traditional Sketching nor CAD offer favourable levels of Ambiguity in this tool-use condition during the Early-Middle phases of the design process.

The negative correlation between these two DTCs suggests that Digital Sketching could be beneficial for designers to utilise in this tool-use condition. This is due to the moderate nature of Digital Sketching on both Level of Aesthetics and Ambiguity. If Digital Sketching is used wisely, a preferable balance between these two DTCs can be achieved in *external communication*. For example, even though Ob2 did not create any design variations in the sessions, he justified his choices based on the clients' requirements in the follow-up interviews. The reasons why the levels of Ambiguity offered by Digital Sketching are more favourable in this tool-use condition are explained in Chapter 5 with the interview data.

In summary, the observation results show supportive evidence of the association between Ambiguity and Level of Detail in e*xternal communication* in the Early-Middle design phases in industrial design practice. These two DTCs tend to correlate to each other negatively, and their proposed levels offered across the three tools are given in Table 6.11. To summarise, both interview results and observation results indicate Digital Sketching offers a preferable combination of Ambiguity and Level of Detail than Traditional Sketching and CAD in this tool-use condition, which is further discussed in Chapter 7.

Tool-use Condition: External Communication		
DTCs / Design Tools	Ambiguity	Level of Detail
Traditional Sketching	Generally High	Generally Low
Digital Sketching	Medium-High	Medium-High
CAD Modelling and Rendering	Generally Low	Generally High

Table 6.11 Proposed Association Between Level of Detail and Ambiguity Across the Three Tools in External Communication Based on Interview and Observation Data

6.4 Reliability and Limitations of the Observation Results

In terms of the reliability of the observation results, the coding procedure is considered well-defined with three steps to guide the analysis. The context of each observation session is cross-checked with pre-observation clarifications and follow-up interviews, so that the tool-use conditions of the design activities observed can be clarified, hence minimising the chance of misinterpretation.

At stage 2 of the analysis, the observation content was coded prior to analysis. The used coding methods are mostly objective approaches. Expert judgement is used to code the Level of Aesthetics of the design representations. First, the author's expertise in making the initial judgements is given for clarification. According to Hekkert and Van Wieringen (1998), clear criteria of the examined aesthetics can help with the reliability of the results. In this study, two relatively objective items are included in the criteria, which are line quality and level of realism. Moreover, an inter-rater reliability check was conducted with another independent expert in industrial design who has more than 5 years of industry experience. With the criteria explained (Hekkert and Van Wieringen, 1998), consensus between the coders was reached on the first attempt.

There are also some limitations of the observations. First, the sample size of the observation study is relatively small due to the availability of practising designers. In this study, the observations were conducted to reflect designers' natural selection and use of tools and the selection and use of tools of each observation session were not organised by the researcher. Hence, the balanced use of all three tools is difficult to guarantee. The time of each observation session was also kept relatively short to ensure the unobtrusive nature of the observations. As a consequence, the use of the three tools in the sessions is not an even split but a natural result of the designers' own choice. Longer observations with practising designers may reveal more patterns of use and applications of the tools. However, for this study, remaining minimal impact on designers'

work environment is more important for revealing designers' actual patterns of use of the investigation tools in practice. Increased sample size and observation time length could offer a higher chance to observe the use of all three tools in the targeted two tool-use conditions, which can further enrich the results. These limitations are noted and accepted to suit the overall aim and time frame of the study.

In the same way, due to time-frame constraints, the observation results are only used to triangulate the interview results in this study; hence, the analysis of collected materials is as thorough as the interviews. Future studies can be expected using the observation data.

6.5 Chapter Summary

In this chapter, results from observing designers using Traditional Sketching, Digital Sketching and CAD are given. Four groups of targeted Design Tool Characteristics (DTCs) associations discovered from the interviews are examined with the observations. The associations between these DTCs are considered important to further understand the manifestation of Digital Sketching in practice. The observation results also give a clearer image of how Traditional Sketching and CAD manifest in practice and explain some troublesome transitions between these two tools. Thus, observations open up more specific discussions on the use of Digital Sketching in different tool-use conditions, and data from observations triangulated with interview findings form a basis to answer research question 3 – whether or not Digital Sketching could be a transitional tool bridging its neighbouring tools.

The data is first discussed based on the levels of the targeted DTCs offered by the observed tools. Then, based on the study results, comparisons between Traditional Sketching, Digital Sketching and CAD are made for analysing the comparative strengths of Digital Sketching.

The low usage of Digital Sketching in the Early-Middle design phases is evidenced by the observation results, especially in *externalisation*. Level of Detail and Use Cost, and Accuracy and Fidelity, are the two groups of associations explored in this tool-use condition. The observation results suggest that the perception of high Use Cost of Digital Sketching could be associated with the generally high Level of Detail created by it, which can be moderated if the design intent is clear. For example, using colour blocks and free-hand sketching with Digital Sketching are examples of a less time-consuming application. The data also shows Digital Sketching can offer a wider inter-medium range of Accuracy and Fidelity in *externalisation* that bridges the gap between

the relative strengths of CAD and Traditional Sketching.

In external communication, the current use of Digital Sketching in practice is more accepted than in *externalisation*, and the observation results support this pattern of use of Digital Sketching in industrial design practice. It also helps to explain some of the key reasons behind this pattern of use, which could deepen our understanding of this tool so as to utilise it more effectively. As the observation results suggest, Digital Sketching offers a good balance of Level of Aesthetics and Use Cost. Due to the nature of external communication, clients and other non-designer stakeholders are targeted as the audience of the design representations, which can lend more focus to the visual appeal of the design representations.

In general, digital platforms and tools can offer higher resolution than traditional medium, which allows Digital Sketching and CAD to achieve a higher Level of Aesthetics compared to Traditional Sketching. However, according to the interview results, the Use Cost of Traditional Sketching is lower in general while CAD is described as "extremely time-consuming". The observation results suggest that the use of Digital Sketching to balance Level of Aesthetics and Use Cost in external communication can be effective. Digital Sketching seems to have a high digital resolution but is not as time-consuming as CAD, especially in the Early-Middle design phases. From the observation data, Digital Sketching appears to offer a preferable combination of these two DTCs in external communication.

To summarise, the observation results generally concur with some of the findings in the interviews. The four groups of associations between targeted DTCs are examined to answer research question 2 by giving a richer understanding of the patterns of use and applications of Digital Sketching in practice. Figure 6.10 proposes a summary of the four groups of associations across the three tools and the correlations within each association. In Chapter 7, further discussions are developed – based on the combined observation and interview results – to further answer research questions 2 and 3.

Externalisation	Relationship	Traditional Sketching	Digital Sketching	CAD rendering
Level of Detail	↑	Generally Low	Low to High	Medium to High
Use Cost	↑	Generally Low	Low to High	Low to High
Accuracy	↑	Generally Low	Medium to High	Generally High
Fidelity (Required)	↑	Generally Low	Low to High	Generally High

External Communication	Relationship	Traditional Sketching	Digital Sketching	CAD rendering
Level of Aesthetics	↑	Low to Medium	Low to High	Generally High
Use Cost	↑	Generally Low	Low to Medium	Generally High
Level of Detail	↑	Generally Low	Medium to High	Generally High
Ambiguity	↓	Generally High	Medium to High	Generally Low

Fig. 6.10 Summary of the Proposed Levels of Targeted DTCs and Their Associations Across the Three Tools

CHAPTER 7

DISCUSSION OF THE FINDINGS

In this chapter, discussions around the answers to the three research questions are given in order. The research questions are: 1) How to compare Digital Sketching with other design visualisation tools? 2) How does Digital Sketching manifest in industrial design practice during the Early-Middle design phases? 3) Could Digital Sketching be a "pathway" to ease transitions between Traditional Sketching and CAD during the Early-Middle design phases in industrial design? With support from the interview and observation results, discussions are developed in a four-step structure: 1) Answer the research question with evidence from the results, 2) Reflect on results in the context of the literature, 3) Discussion of the validity of the results and answers, and 4) Significance of the answers to the field of industrial design. Some unexpected findings are also discussed; i.e., Section 7.4 presents a finding of how the learning process of Digital Sketching in formal education impacts the patterns of its uses in practice.

7.1 Design Tool Characteristics (DTCs) Framework: The Basis to Compare Digital Sketching With Other Design Visualisation Tools

Regarding the research question 1, the application of using the Design Tool Characteristics (DTCs) framework to compare Digital Sketching with its neighbouring tools in this study demonstrates the framework can work as an approach to compare design tools in 3D design fields. It forms the basis to reflect on how effective the DTCs framework is in terms of guiding the comparisons between Digital Sketching and its neighbouring tools in industrial design practice.

7.1.1 Advantages of the DTCs framework

Existing literature shows that the use of frameworks to compare tools is feasible, especially Universal Tool Characteristics (Self et al., 2009). However, as is shown in Chapter 2, existing frameworks are not comprehensive enough to give in-depth understanding of the tools. The study results suggest that the DTCs framework is a comprehensive and effective framework to compare design visualisation tools in the industrial design field, including understanding and evaluating emerging design tools and techniques.

Three advantages of the framework are observed during the study and reflected in both the interview and observation results:

- **More Comprehensive**
  First of all, compared to other existing design tool characteristic frameworks that were reviewed, the DTCs framework is more comprehensive. It includes 24 individual design tool characteristics identified and extended through the literature review while other frameworks are more generalised (Pei et al., 2011; Self et al., 2009). The extensiveness of the DTCs framework enables us to have in-depth point-to-point comparisons between design tools and techniques. In other words, the DTCs framework offers a more comprehensive way to understand and compare design tools with specifics. As an example, from the interview results in Table 5.8, the differences between the key DTCs (the most frequently mentioned DTCs by the participants) of Digital Sketching and its neighbouring tools allow the differences of the tools to be more noticeable than simply comparing them with a limited number of generalised characteristics. In other words, the nuance of the tools is also reflected in the different inter-associations of the key DTCs.

  Besides, the Design Tool Characteristics (DTCs) framework allows the discovery of deeper insights from the design tool comparisons and prompts discoveries beyond the point-to-point comparisons. From the study, understanding a tool or mapping a tool with the DTCs framework helps to view a design tool with a higher fidelity (more dynamic and realistic) while remaining in an organised complex level than when using more high-level frameworks. As is illustrated in Figure 7.1, when conducting a comparison of two design tools, the increased number of DTCs offered by the framework means more nodes in the comparison system, which can enable the results to show a more multifaceted and comprehensive view of the tools. Similarly, the nuances in the tools can be identified and presented in an organised way (if it is desired).

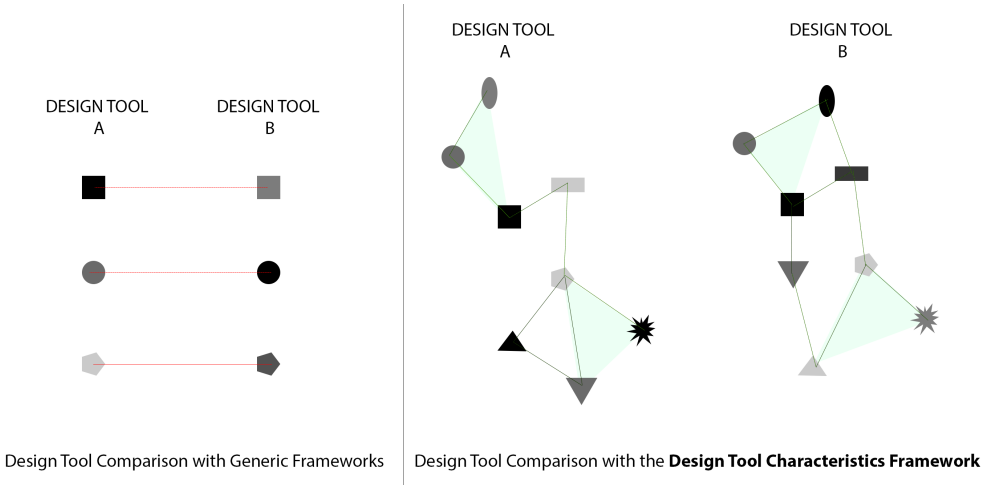


Fig. 7.1 Comparing Design Tools With Generic Frameworks Versus With the DTCs Framework

For example, the DTCs framework contributes to the discovery of the associations of different DTCs under different tool-use conditions in Chapter 5 Section 5.10. This allows the analysis of Digital Sketching and its neighbouring tools to be more systematic and supported with specific evidence, and also allows more macroscopic comparisons between patterns beyond the point-to-point comparisons (see patterns of key DTCs in different tool-use conditions illustrated in Figures 5.20, 5.21 and 5.22).

- **Universal Characteristics**
  Even though the denseness of the framework is significantly increased compared to other existing design tool characteristic frameworks, all the characteristics in the DTCs framework remain universal, which ensures the effectiveness of using the framework for conducting comparisons of design tools. During the creation of the DTCs framework, the design tool characteristics are firstly discovered from a detailed literature review in 3D fields to ensure each characteristic to be universal and extended with the researcher's working experience and observation. In Chapter 2, the references and examples of each of the DTCs illustrate that they are shared in different levels by most of the tools in 3D design fields. Similarly, the interview and observation results concur with the universality of the DTCs in the framework in theory. From the interview and observation results, most of the mentioned DTCs have appeared in more than two design tools. Table 7.1, below, summarises this distribution of mentions and/or observations DTCs in the framework across the three tools investigated.

No.	Design Tool Characteristics	Traditional Sketching	Digital Sketching	CAD
1	Ambiguity	In/Ob	In/Ob	In/Ob
2	Lateral Transformation	In/Ob	In	In
3	Vertical Transformation	In/Ob	In/Ob	In/Ob
4	Level of Commitment	In	In	In
5	Level of Aesthetics	In/Ob	In/Ob	In/Ob
6	Accuracy	In/Ob	In/Ob	In/Ob
7	Problem Re-framing	In/Ob	In	In/Ob
8	Amount of Representations	In/Ob	In/Ob	In/Ob
9	Immediacy	In/Ob	In/Ob	In/Ob
10	Flexibility	In/Ob	In/Ob	In/Ob
11	Mobility	In/Ob	In/Ob	In/Ob
12	User Accessibility	In/Ob	In/Ob	In/Ob
13.1	Level of Detail (Engineering)	In/Ob	In/Ob	In/Ob
13.2	Level of Detail (Aesthetic)	In/Ob	In/Ob	In/Ob
14	Holistic View of Objects	In/Ob	In/Ob	In/Ob
15	Compatibility	In/Ob	In/Ob	In/Ob
16	Fidelity	In/Ob	In/Ob	In/Ob
17	Learning Cost	In	In	In
18	Use Cost	In/Ob	In/Ob	In/Ob
19	Tendency to Mix Tools	In/Ob	In/Ob	In/Ob
20	Emotional Commitment to Ideas	In/Ob	In	In
21	Expectation	In	In	In
22	Expertise	In	In/Ob	In/Ob
23	User Loyalty	In	In	In
24	User Share	In/Ob	In/Ob	In/Ob

Table 7.1 DTCs Mentioned (In) and/or Observed (Ob) Across the Three Tools in the Study

- **Combined Perspectives**

  The new DTCs framework includes two perspectives to guide the analysis of design tools and compare tool-use activities; namely, the tool's capabilities and tool users. As is shown in Chapter 2, Subsection 2.3.2, design tool-use activities are influenced by both the design tools and the designers (users of the design tools). To ensure the effectiveness of the comparisons of design tools, it is important to include both perspectives in the process. Existing design tool characteristics frameworks have paid a limited level of attention to these two different perspectives (Purcell and Gero, 1998; Self, 2011). Therefore, the new DTCs framework has combined the two perspectives in the framework and grouped the universal design tool characteristics accordingly as Capability-related Characteristics of Design Tools (CCs) and User-related Characteristics of Design Tools (UCs). The interview and observation results suggest that it can be more effective and objective when the two perspectives are both considered in the experiment. During the interview observation studies, the Capability-related Characteristics of Design Tools (CCs) were used to map the data regarding the tools themselves to more analytical and comparable levels of DTCs. At the same time, the User-related Characteristics of Design Tools (UCs) helped to identify the influences of the in-

dividual users on their given interview comments and tool-use behaviours. For example, according to the results, the low User Loyalty and Expertise (both are UCs) of users with Digital Sketching are indicated as influencing factors on the acquirements of high Fidelity input and high Use Cost (CCs) of Digital Sketching in Externalisation.

To summarise, combining the perspectives of design tools and design tool users, the new DTCs framework offers a more comprehensive list of universal design tool characteristics that are related to design tool-use behaviours and activities in 3D design fields. Using the DTCs framework, the design behaviours from the interview study and the observation study are transferred to comparable data, from which the most frequently mentioned DTCs are highlighted as the key DTCs for comparing design tools and their manifestations. The study results show how these comparable key DTCs are effective in mapping out how the design tools are valued and used by different designers. The comprehensiveness of the DTCs framework can enable the opportunity to look not only beyond the individual characteristics but also compare the design tools in a multifaceted view of associations of DTCs if desired.

Hence, comparing different design tools using the new DTCs framework can deepen understanding of the uses of design tools, initiate in-depth discussions and promote more efficient uses of the tools in the future.

7.1.2 Limitations and Significance of Using the DTCs Framework to Compare Digital Sketching

The results from both interview and observation studies have supported the utility of the Design Tool Characteristics (DTCs) framework. When using the DTCs framework to map the interview data, the results are clearly compared between Digital Sketching and its neighbouring tools. Also, the result of the inter-rater reliability test (0.98/1) supports the accuracy and effectiveness of interpreting and coding with the DTCs framework between different coders. During the interview and observation studies, some benefits and limitations of using the DTCs framework to compare Digital Sketching with its neighbouring tools are identified as follows:

Limitations of Using the DTCs Framework

- **Interlinked Characteristics**
  As the more comprehensive list of DTCs in the framework enables more detailed comparisons, the differentiation of certain interlinked DTCs can be difficult in

the coding/mapping process. This is also noticeable in the inter-rater reliability test even though the test result meets satisfaction. For example, the results of tool types and tool-use conditions inter-rater reliability are 1/1 while the result of individual DTCs inter-rater reliability is 0.94/1. The initial result of individual DTCs inter-rater reliability was 0.8/1 when considering the interlinked DTCs as a group. Table 7.2 shows a few examples where the independent coder tended to nominate more than one of the DTCs regarding a single interview comment; most of these paired-up DTCs are identified as interlinked DTCs. Therefore, some interlinked DTCs are suggested in Chapter 5, Section 5.10 as a preliminary guideline for the association patterns of the DTCs under different tool-use conditions in the industrial design field. The full list of the DTCs framework enables the highest resolution coding and analysis regarding the design tools, but the interlinked DTCs groups can also help to form lower resolution coding and analysis, which can be used to generate a more multifaceted view of the tools. For example, in Figure 5.20, the interlinked key DTCs in Externalisation indicate a hierarchy of the resolutions of analysis and coding. Here, the lower resolution of analysis only includes Fidelity, Level of Detail, Level of Aesthetics and Use Cost that can be desirable when the general manifestation of the tool is preferred to specific detail in a project. Vice versa, the full list of DTCs in the framework can assist to analyse and compare the design visualisation tools more precisely on any of the universal characteristics.

Tool	Interview Comment	Tool-use Condition	Design Tool Characteristic
CAD	With Solidworks, you really need to define the set of measurements and the actions you want to take, you don't have that much freedom in order to create multiple ideas.	Externalisation	Flexibility Vertical Transformation
Traditional Sketching	I think the most basic one would be just a pen and paper to start sketching and ideating around the product or what you are designing and trying to get as many ideas as possible down on the paper.	Externalisation	Lateral Transformation Immediacy
Traditional Sketching	With the colleagues, mostly hand sketches. It's fast I guess, and then if there's something that you want to change in the sketch you can just draw over it to convey the point.	Internal Communication	Flexibility User Accessibility

Table 7.2 Examples of Interlinked DTCs in Inter-rater Reliability Test

- **Qualitative-led Approach**

  The DTCs framework is initially a qualitative-led research method that potentially requires a customised coding scheme for each project. In this project, the results from the interview and observation studies are driven from qualitative-focused data and the coding schemes are also specifically built. Measurement of the data can likewise be difficult as a more qualitative method, the DTCs frame-

work, is used in the coding process. In future studies, the method of using the DTCs framework could be further optimised and made more adaptable for various types of research projects. The DTCs framework will be further developed, and a more quantitative ranking system may be adopted in the near future to balance the qualitative-led approach. Hence, a more generalised and mature method or guideline of using the DTCs framework to understand and compare design tools in 3D design fields can be expected.

Significance of the DTCs Framework

- **For Researchers**
  Results from the interview and observation studies in this project suggest that using the DTCs can be an effective way to compare different design visualisation tools in the 3D design field, especially in industrial design. As mentioned above, the advantages of the new DTCs framework are that it is more comprehensive and universal. By combining perspectives from the tools and the users, it can help researchers in the field to build more systematic in-depth understandings, comparisons and evaluations of different design tools. The new DTCs framework can be applied not just to existing tools but also to emerging and leading-edge design visualisation tools; i.e., design tools based on Augmented Reality and Virtual Reality platforms – which before the creation of the DTCs framework could be tricky to compare. For further examples since the creation of the DTCs framework was published, it has been used to understand a new hybrid tool – Digital Sketch Modelling – in another study: (Ranscombe et al., 2019).

  In summary, comparisons across combinations of traditional design tools, emerging design tools and hybrid design tools can be guided by the new DTCs framework.

- **For Design Tool Developers**
  Similarly, for design tool developers, evaluations of a tool using the DTCs framework may help to obtain more detailed and targeted feedback from the users regarding which part of a tool needs to improve and why. The characteristics in the new DTCs framework are also sufficiently comprehensive and general to inform any leading-edge design tools and tools of the future that are fundamentally different from existing common design tools. Therefore, the use of the DTCs framework to compare design tools can contribute to picturing a better future for design visualisation tools in general by being able to understand the tools in more detail – including leading-edge design tools.

- **For Design Students/Designers**

  In the industrial design field, as well as other 3D design fields, new design tools are developed every day. For design students and practising designers, it can be challenging to decide which new tools to learn, to use, and when to use in their design processes and practices. The DTCs framework can encourage learning and use of emerging design tools by offering a method to compare their strengths and weaknesses. In other words, more comprehensive and comparable manifestations of these emerging design tools can be grasped – targeted guidelines for practising designers and design students can then be expected. Similar to the Prototype Canvas (Lauff et al., 2019) on prototyping tools, the outcomes of using the DTCs framework on understanding emerging design tools would be guidelines for planning purposeful and suitable uses of these tools.

  All in all, more effective and efficient uses of emerging design tools can be expected after their suitable roles in the design process are mapped by the designers using the DTCs framework, which could ultimately help to reduce the sunk cost and free up resources in design practice.

- **For Design Educators**

  The challenge faced by design education is the rapidly developing world of design tools. In other words, design educators also need to choose which tools to deliver to our future designers when facing the challenge of a continuing updating pool of design tools. Especially for educators trying to embrace new technologies and tools, it could be difficult to make prompt and wise choices and updates on tools and methods to deliver in their daily teaching activities. The DTCs framework may offer a chance for designer educators to catch up with the updates in the industry by helping to build an up-to-date and high-quality curriculum guided by in-depth understandings of the new tools. As a practising educator, the author also plans to evaluate some Virtual Reality design visualisation tools with the new DTCs framework that can be beneficial to be introduced to industrial design education.

In this project, according to the results, the use of the DTCs framework to compare Digital Sketching with Traditional Sketching and CAD in industrial design practice is effective since the framework includes a considerably comprehensive number of universal design tool characters in 3D design fields from both design tool and design tool user perspectives. The study suggests the Design Tool Characteristics (DTCs) framework is an approach to understand, compare and evaluate different design tools in 3D design fields, including leading-edge and hybrid design visualisation tools, which can benefit not just design researchers but also designers, design students, design educators

and design tool developers.

Optimisations and development of the framework are planned in future studies to validate and give a more mature method or guideline so it can be easily used and adapted by other applicable studies.

7.2 Manifestation of Digital Sketching in the Early-Middle Phases of Industrial Design

In this project, the interview study was primarily conducted to understand how Digital Sketching manifests in practice during the Early-Middle phases in the industrial design process (research question 2). It also forms a basis of understanding of Digital Sketching and its neighbouring tools to discuss answers to research question 3. From the interview results, some essential groups of Design Tool Characteristics (DTCs) were targeted for further examination with an observation. The observation aims to enrich the understanding of the manifestation of Digital Sketching in industrial design practice. In this study, the manifestation of Digital Sketching is defined as the patterns of its use in industrial design among practising designers.

The Design Tool Characteristics (DTCs) framework is used to interpret and analyse participants' opinions and behaviours so an in-depth understanding of the patterns of use of the investigated tools can be realised. Comparisons across the three tools were made based on their most frequently mentioned DTCs and the observed selected associations of essential DTCs.

As with results presented in Chapters 5 and 6, the discussion follows the four design tool-use conditions identified: *externalisation*, *external communication*, *internal communication* and the *learning process*. This working category is provided to guide the discussion by clarifying the context, purpose and aim of the use of design tools. Hence, the answers to the patterns of use of Digital Sketching can be condition-specific and applied by the community. Therefore, the discussion in this section is aligned with the order of these categories of tool-use conditions. Discussion of the manifestation of Digital Sketching is structured from the perspective of achieving **effective design visualisations** and conducting **timely efficient design processes/activities**. It is assumed that practising designers seek not only to create highly effective visual communication but also to do so in a time- (and hence budget-) efficient manner. Using these two perspectives thus allows the discussion of the patterns of use of tools to include two important motivators/considerations in designers' selection and use of design tools. Hence, a comprehensive understanding of the way Digital Sketching manifests in practice alongside

Traditional Sketching and CAD can be achieved.

Unless noted explicitly, discussion in this section is within the scope of the **Early-Middle phases** in the industrial design process.

7.2.1 Patterns of Use and Applications of Digital Sketching in Externalisation

Compared to Traditional Sketching, Digital Sketching is considered as a creativity-inhibiting design visualisation tool to a certain degree according to some studies (Eissen and Steur, 2012; Stones and Cassidy, 2010, 2007; Bilda and Demirkan, 2003; Won, 2001; Goel, 1995), in that it may cause design premature fixation during the earlier stages of the design process, as with CAD (Shih et al., 2015; Ibrahim and Rahimian, 2010; Robertson and Radcliffe, 2009). Similar to the literature, the uses of Digital Sketching empirically observed in the daily practice of many students and designers are focused on polishing up more settled design concepts after the earlier phases of the design process.

However, studies in the literature indicate the creativity inhibition from Digital Sketching could be related to the stereotyped patterns of use of this tool rather than the tool itself (Evans and Aldoy, 2016; Stones and Cassidy, 2010). The results from this study further support that Digital Sketching could be an effective tool for *externalisation* in the Early-Middle Phases in industrial design practice when it is used with clear purposes and suitable methods.

The theoretical potential of Digital Sketching in this tool-use condition in the Early-Middle design phases is firstly supported by findings from the *review-based descriptive study I* stage of the study. It is documented in Chapters 1 to 3 and further summarised and discussed in Chapter 4.

Moreover, the interview and observation results from the *comprehensive prescriptive study* stage give more support to the potential patterns of its use in the Early-Middle design phases for externalisation. A discussion based on the results is given from the perspectives of efficiency and the resulting effectiveness of using Digital Sketching for externalisation.

▼ Time Efficiency of Using Digital Sketching in Externalisation

The efficiency of Traditional Sketching is highlighted by both the *review-based descriptive study I* (Booth et al., 2016; Ibrahim and Rahimian, 2010; Bilda et al., 2006; Tang, 2002; Fish and Scrivener, 1990) and the *comprehensive prescriptive study* in this re-

search project as one of its major advantages for *externalisation*. As in Figure 5.16 in Chapter 5, all the participating designers are happy with the low Use Cost (high time efficiency) of Traditional Sketching in assisting visualisation in this tool-use condition. Similarly, the Use Cost of Digital Sketching and CAD has been perceived as relatively negative compared to Traditional Sketching. This perception may inhibit the use of Digital Sketching in this tool-use condition when the widely-accepted rule of design visualisation under this tool-use condition is "quantity over quality", "fast" and "messy".

In other words, one of the major concerns of using Digital Sketching in *externalisation* is related to its time efficiency when conducting the visualisation activities. The results from the interview and observation studies highlight certain characteristics that are related to the time efficiency of using Digital Sketching, which also indicate potential approaches to monitor the level of efficiency when using Digital Sketching in *externalisation*.

According to the results, Digital Sketching appears to offer a wider range of levels of these DTCs compared to Traditional Sketching, which could be used in a more balanced way for better efficiency. However, this wider range of levels on these DTCs can be a double-edged sword that also inhibits the time efficiency. For example, when using Digital Sketching in *externalisation*, designers may have a higher Expectation on the resulting Level of Detail and Level of Aesthetics than is necessary for this tool-use condition. Consequently, they may spend more time on the visualisation activities with Digital Sketching.

It is contended that Digital Sketching could be employed in this tool-use condition with a low Use Cost as long as the mindset of using it is similar to that for Traditional Sketching. In other words, justifying the Expectation on the Level of Aesthetics and Level of Detail to an appropriate level and not demanding a high Fidelity (clear mental image) of the design beforehand.

As a demonstration, in Figure 7.2, the author demonstrated using both Traditional Sketching (Left: ballpoint pen on paper) and Digital Sketching (Right: Photoshop on a Wacom Cintiq 24") to externalise rough ideas on designing the form of a water bottle. A similar mindset of using both tools is adopted in this demonstration; namely, keeping a similar Expectation of the resulting visualisations on Level of Aesthetics and Detail. Besides, the demonstration started with no preset image of the design (keeping low required Fidelity) for both tools. The time spent on generating three rough forms is similar, around 3–3.5 minutes (not including the time to set up the tools) for both Traditional Sketching and Digital Sketching.

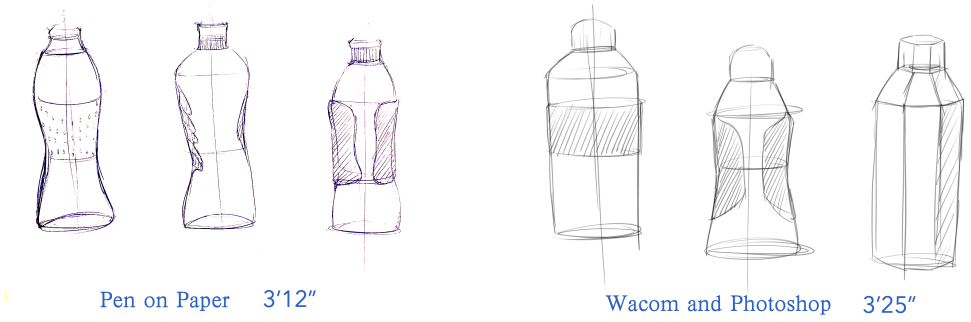


Fig. 7.2 Demonstration: Comparing Efficiency of Digital Sketching Versus Traditional Sketching in Externalisation (Author's Own)

The results from the literature and experiments in this study suggest that, when the tool is available, time efficiency using Digital Sketching in *externalisation* is possible if it is used in a manner which balances four DTCs: Expectation, Level of Aesthetics, Level of Detail and the required Fidelity.

Besides, when the focus of externalisation shifts from Lateral Transformation in the Early phase (e.g. in Figure 7.2) to Vertical Transformation in the Middle phase, the study suggests the time efficiency of Digital Sketching can be even higher than Traditional Sketching. This is partially due to its positively rated Flexibility (see Chapter 5). Therefore, wisely using the Flexibility for Vertical Transformation and being aware of the Level of Detail can further control the Use Cost of Digital Sketching in practice in this tool-use condition. According to the experiment results, features in Digital Sketching that can facilitate the Flexibility for Vertical Transformation (including but not limited to) are as follows:

- Copy and Paste/Duplicate/Array
  These features enable quick multiplication of one concept and accordingly work on design variations (Vertical Transformation).
- Image Adjustment/Advanced Colour Panels
  These features enable quick previews of different colour schemes, hues, contrasts, etc.
- Image Transformations/Scale and Re-scale
  These features enable quick tweaks of the design concept and give stimuli to generating more concepts/design solutions.
- Layers, Locks and Masks
  These features could enable fast testing of textures and materials using online libraries or image references on the design visualisations of one design concept.

"Block CAD" is frequently mentioned in the interviews as an approach for CAD to assist more time-efficient externalisation. It can be used for either easy perspective drawing or more accurate proportions. The layers and masks in Digital Sketching can save a designer's time by adopting "Block CAD" more directly rather than printing the CAD renderings out then tracing over the model with pen and paper.

▼ Effectiveness of Using Digital Sketching in Externalisation

Traditional Sketching is suggested as the widely accepted design visualisation tool in externalisation during the Early-Middle phases in the industrial design process by both literature review and the interviews. At the same time, Digital Sketching is not perceived very favourably to be used in this tool-use condition due to its ineffectiveness. The results suggest that certain key DTCs of Digital Sketching – some of the most frequently mentioned characteristics in the interviews – have impacts on the resulting visualisations. These key DTCs are nominated for further discussion on the patterns of use of Digital Sketching.

Certain key DTCs of CAD Modelling are also nominated for discussion, as evidence from the literature shows that CAD Modelling is also not well accepted as a tool in externalisation compared to Traditional Sketching. The nominated DTCs from the three tools investigated in this study could give a fairly comprehensive understanding of what DTCs are desired in externalisation, from which the patterns of use of Digital Sketching can be argued.

As presented and briefly discussed in Chapters 5 and 6, the key DTCs of Digital Sketching that have **positive impacts** on generating effective results in externalisation include:

• Level of Aesthetics, Flexibility and Vertical Transformation

Concurrent with the findings from the literature in Chapter 2, the interview and observation results suggest that the Level of Aesthetics offered by Digital Sketching may be a double-edged sword. On one hand, the high Level of Aesthetics that can be achieved with Digital Sketching could encourage the designers to really explore some creative or far reaching design directions compared to the more rigid CAD modelling or the more skill-requiring Traditional Sketching.

In that sense, Digital Sketching can effectively stimulate design transformations in externalisation, especially for Vertical Transformation.

On the other hand, the high Level of Aesthetics may inhibit the Lateral transformation

if used without awareness of its "danger", since designers tend to immerse themselves with continuously beautifying one idea (just because they can with Digital Sketching). However, the study considers the Level of Aesthetics offered by Digital Sketching a contributing factor to its overall effectiveness in externalisation. This is because it not only offers a high Level of Aesthetics but also supports design transformations and visualisations. There is a moderately wide range of Levels of Aesthetics offered by Digital Sketching; e.g., low levels in Figure 7.2.

As is shown in Chapter 5, the Flexibility of Digital sketching is one of the most mentioned key DTCs in Digital Sketching in this tool-use condition. It also has the highest reference of positive sentiments from the participants (see Figure 5.16). In terms of effectiveness, having high Flexibility in externalisation could stimulate effective Vertical Transformations for the development of the design ideas. For example, designers can use Digital Sketching's features by quickly multiplying the original design idea, then tweaking the results with visual effects, or easily adding, subtracting, detailing, modifying or rescaling the design idea.

Similarly, the results also indicate that there are certain DTCs of Digital Sketching that attracted **concerns** to its effectiveness in externalisation for designers, which are primarily related to a few User-related Characteristics of Design Tools (UCs) (as follows).

• User Expertise and User Loyalty

According to the study, the User Expertise of Digital Sketching is considered one of the major concerns when using Digital Sketching in externalisation in the Early-Middle design phases. As the tool-use activities are primarily focused on creating or detailing design ideas in this tool-use condition, the User Expertise of the tool is critical for effectively and fluently externalising the mental images to the physical world. As interview participants state: "I am not sure it's just me or Digital Sketching". They are not satisfied with the effectiveness of using Digital Sketching in externalisation. Some of them feel the urge of practising the tool, "I need to use it [Digital Sketching] more", to gain confidence in using it so they do not need to "risk it" by breaking the creative flow or losing the ideas before visualising them.

Compared with Traditional Sketching and CAD, the generally lower User Expertise of Digital Sketching among participated designers is a result of many factors; i.e., the lower User Share in previous education systems and lower User Loyalty towards the tool. However, with the increasing User Share in design education, User Expertise could be increased among future designers. Hence, its negative impact on the effectiveness of using Digital Sketching in externalisation during the Early-Middle design phase in

industrial design may be less of a concern.

The results from interview and observation studies also indicate there are other less frequently mentioned DTCs of Digital Sketching that could have impacts on its effectiveness. More investigations are needed to test these potentials. These DTCs are including but not limited to:

• Accuracy and Ambiguity

In *externalisation*, Accuracy and Ambiguity are considered as a pair of DTCs that are in conflict with each other to a certain degree. Based on the findings from the literature review in Chapter 2, Ambiguity is regarded as an essential characteristic in externalising design ideas in the earlier phases of the industrial design process. However, the results of this study show that both Ambiguity and Accuracy are important for achieving effective design visualisations in the Early-Middle phases in practice. This is partially due to many of the real-world industrial design projects having restrictions on design concepts from the very beginning; i.e., dimensions of the internal components or requirements from the applied technologies. The combination of Accuracy and Ambiguity of Digital Sketching seems to offer a more positive influence on supporting effective externalisation compared to its neighbouring tools.

As is shown in Table 5.8, Accuracy is identified as one of the key DTCs in this tool-use condition for both Traditional Sketching and CAD but with bipolarised sentiment results. This result shows the need for a certain level of Accuracy for "getting the scale right" in real-world design projects in the Early-Middle phases, especially design projects with fixed internal technologies and components. Interview participants suggested the Accuracy of Traditional Sketching is below satisfaction while CAD offers a high level of Accuracy. From the interview, there were insufficient data regarding the Accuracy of Digital Sketching in this tool-use condition. However, from the author's observation at workplaces, the digital platform and software of Digital Sketching could enable a higher level of Accuracy than Traditional Sketching if needed. For example, Figure 7.3 shows that the preset shapes and freehand drawn shapes in Digital Sketching (Adobe Photoshop CC 2019) have numeric dimensional properties that can be easily viewed, controlled and modified.

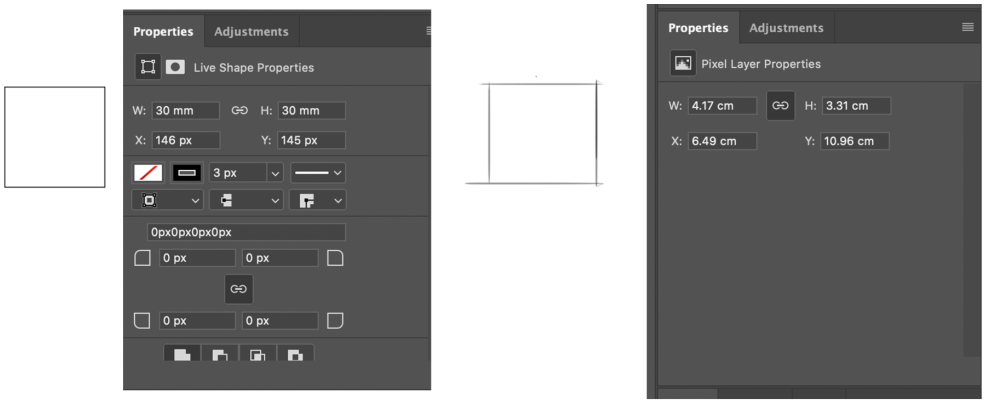


Fig. 7.3 Features That Enable Accuracy in Digital Sketching

However, the literature findings also suggest that the Ambiguity could decrease when the Accuracy is increased. Finding a balance between Ambiguity and Accuracy is important but tricky in *externalisation*. Traditional Sketching benefits from its low Accuracy but high Ambiguity, which ensures its effectiveness in this tool-use condition according to relevant studies. But the increasing demand of Accuracy in real-world design projects may challenge the effectiveness of Traditional Sketching nowadays.

On the contrary, CAD Modelling used to be considered as a less effective tool in *externalisation* due to its low Ambiguity and high Accuracy, but the interview results indicate that CAD Modelling can also offer a lower level of Ambiguity with creative patterns of use. For example, the use of "Block CAD" can be more supportive in Lateral Transformation and Problem re-framing during *externalisation*. This finding inspires the reconsideration of the perceived Ambiguity of Digital Sketching found in the literature. The study indicates that the Ambiguity offered by Digital Sketching could also be a positive characteristic in supporting effective *externalisation* rather than a negative one. It suggests that the Ambiguity of Digital Sketching can vary from as low as Traditional Sketching to a medium-high level as moderately polished CAD renderings.

Therefore, when Digital Sketching is used with low levels of Ambiguity, it can effectively support Lateral Transformation and Problem re-framing in *externalisation*. It also offers the option to be more accurate (if desired in the design project) with numeric controls. Digital Sketching can also be more easily used with "Block CAD" than Traditional Sketching due to its good Compatibility. Hence, Digital Sketching could offer relatively high Accuracy yet still be ambiguous and flexible as a sketching tool for designers to further develop their design ideas, which are not very plausible in CAD after the "Block CAD" stage, according to the interview participants.

• Holistic View of the Object and Immediacy

As in Table 5.8, the Immediacy offered by Traditional Sketching and the Holistic View of the Object offered by 3D CAD Modelling in externalisation during the Early-Middle phases in the industrial design process both have positive sentiment results from the interviews. A lack of mentions of these two characteristics of Digital Sketching indicates that it may need attention from the tool development perspective on adjusting these two DTCs of Digital Sketching to support design visualisations in this tool-use condition.

The Compatibility of Digital Sketching is considered good for working with CAD, which could compensate for the lack of a 3D Holistic View of the Object. The Immediacy of Digital Sketching, in terms of the connection between a digital stylus with a tablet, is improving constantly in both hardware (Wacom Cintiq pro, iPad pro, etc.) and software (Adobe Photoshop, Sketchbook Pro, Procreate, etc.) development. Advanced settings of brush tools in the software can mimic real-pen using experience, and touch-sensitive hardware screens can simulate the touching/rotating of real paper and canvas. For instance, in Figure 7.4, a Digital Sketching device is incorporating the use of real pen and paper (Wacom Smartpad).

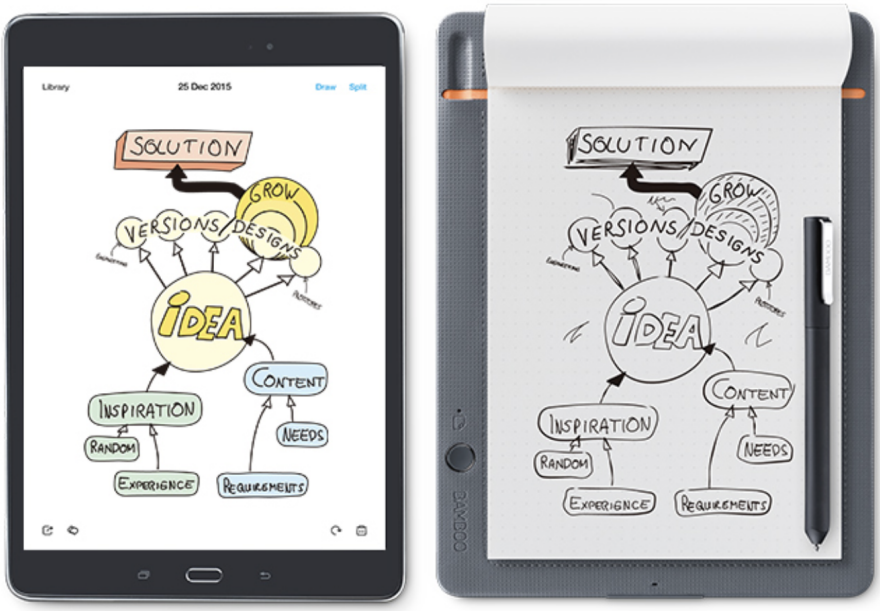


Fig. 7.4 Incorporating Traditional Sketching in Digital Sketching (Wacom, 2020)

Moreover, the psychological attachment of pen on paper and the difference between pen-on-paper and stylus-on-tablet may be less noticed or cared about by future generations/designers as they grow up with the digital tools, or they were already introduced to them early enough in their formal education so they are accustomed to the differences.

▲ Summary: The Manifestation of Digital Sketching in Externalisation

The experiment results in this study suggest that the manifestation of Digital Sketching in *externalisation* is as follows:

The current use of Digital Sketching in *externalisation* is less than Traditional Sketching and CAD. Creative uses of Digital Sketching could be encouraged in this tool-use condition, which should be based on its DTCs to ensure the time efficiency of the design visualisation. Some User-related Characteristics of Design Tools (UCs) of Digital Sketching could have an impact on the time cost of using Digital Sketching that designers should be aware of. These are the User Expertise of the designers that use the tool, their User Loyalty towards other visualisation tools, and their User Accessibility to the tool. To facilitate better time efficiency of Digital Sketching in this tool-use condition in the Early-Middle phases during the industrial design process, the above UCs also require attention and improvements from the tool users and developers.

If the designers have no strong preference or experience over other tools and have an above-beginner level of User Expertise (i.e. completion of one course) with Digital Sketching, they may use it for achieving effective visualisations. It offers potentially more balanced combinations of Level of Aesthetics, Flexibility, Ambiguity and Accuracy than seen in Traditional Sketching and CAD. It could be used for flexible, aesthetic, lateral and vertical transformations of design ideas.

Finally, Digital Sketching may also have potential to further support effective *externalisation* with more and more developed technology. For example, the technological delay between the designers and the sketching tablets could be narrowed down, and more holistic and detailed views of the design ideas can be offered by Digital Sketching. Ideally, less emotional commitments would be triggered by using Digital Sketching in the Early-Middle phases compared to CAD modelling.

7.2.2 Patterns of Use and Applications of Digital Sketching in External Communication

According to the experiment results, Digital Sketching is relatively well-accepted in *external communication* in the Early-Middle phases in practice, which concurs with the theoretical potential of this tool shown in Chapter 2. Compared to Traditional Sketching and CAD Modelling, the patterns of use and applications of Digital Sketching are considered to be time-efficient for achieving effective design visualisations when the purpose is primarily focused on explaining, displaying and presenting ideas to clients and other stakeholders during the Early-Middle phases. The manifestations of all these

three tools in this tool-use condition are compared and discussed based on the experiment results. All in all, the interview and observation results suggest that, with less time investment, designers can use Digital Sketching to convey their design ideas, reserve space for design refinement and gain constructive feedback with impressive and detailed design visualisations in *external communication*.

▼ Time Efficiency of Using Digital Sketching in External Communication

Similar to the discussion of time efficiency in *externalisation*, the time efficiency in *external communication* is defined as the time-efficiency in creating design visualisations for clients and other non-designer stakeholders. Based on the key DTCs from the interview results in Section 5.10.2, the primary efficiency-related key DTCs are determined as the Use Cost and Flexibility, which can be influenced by other DTCs; i.e., Level of Aesthetics, Fidelity, Level of Detail and User Expertise. For clarity, discussion on the patterns of use and applications of Digital Sketching regarding time efficiency in *external communication* is also led by these characteristics.

• Use Cost, Flexibility and Level of Aesthetics

In Section 3.3.2, the literature review results suggest that the Use Cost is preferably low during the Early-Middle design phases in industrial design in general, even when the tool-use activities are conducted for generating visualisations for the clients. In Chapter 5, Subsection 5.9.2, the interview results suggest that Level of Aesthetics and Use Cost are two of the four shared key DTCs across Traditional Sketching, Digital Sketching and CAD in *external communication* in practice. Both the interview and observation results indicate that there could be a proportional correlation between the Level of Aesthetics offered by the tool and the associated Use Cost of it in this tool-use condition. It is worth noting that the gradient of the correlation offered by Digital Sketching could be more preferable in *external communication* during the Early-Middle phases than its neighbouring tools. In detail, based on the interview results and experience, the interpretation of the potential correlations between the Level of Aesthetics and Use Cost of the three tools are illustrated in Figure 7.5.

The interview results indicate that the gradient of this correlation between Level of Aesthetics and Use Cost in Digital Sketching could be more moderate and suitable for achieving a fairly high Level of Aesthetics for communication with clients, which would be preferred by both parties during the Early-Middle phases in industrial design practice. As discussed in Subsection 6.3.4, the observation results also suggest that Digital Sketching can offer a wider range of choices on Level of Aesthetics with more moderate Use Cost compared to Traditional Sketching and CAD in this tool-use condition.

In Figure 7.5, the sharp increases of Use Cost in Traditional Sketching usually happen at a relatively lower Level of Aesthetics in *external communication* compared to Digital Sketching according to the literature review and experiment results. This phenomenon could be related to the low level of Flexibility offered by Traditional Sketching for further modifying existing design visualisations in *external communication*. For example, there is no undo/redo when a mistake is made in Traditional Sketching, and designers are more reluctant to show mistakes in the more presentation-focused *external communication* compared to the more idea-focused *externalisation*. Benefiting from its digital platform, Digital Sketching may offer more Flexibility in this aspect in the *external communication* compared to Traditional Sketching. Hence, as illustrated in Figure 7.5, the sharp increases in Use Cost of Digital Sketching are considered to happen at a relatively higher Level of Aesthetics.

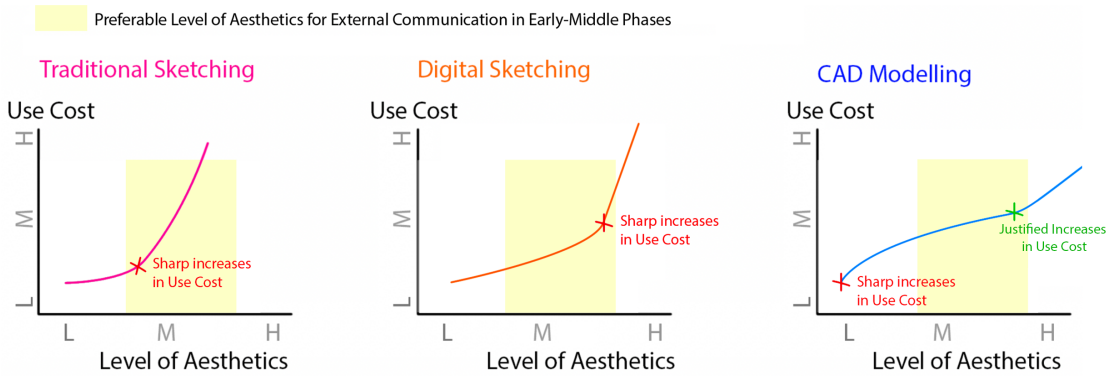


Fig. 7.5 Figurative Illustration of the Potential Correlations of Level of Aesthetics and Use Cost in Traditional Sketching, Digital Sketching and CAD in External Communication in Early-Middle Design Phases in Industrial Design

Moreover, the experiment results concur with the literature review that the Use Cost of CAD could increase sharply at a low Level of Aesthetics. In the Middle-Late phases of the design process, the higher Use Cost is justified when CAD is used for reaching the photorealistic Level of Aesthetics for final delivery in *external communication*. However, it is not preferred by the designers in the Early-Middle design phases. The advantage of using Digital Sketching with potentially lower Use Cost for a higher Level of Aesthetics also stops at a point when the higher Use Cost of CAD in *external communication* is balanced out for its photorealistic output of Level of Aesthetics.

As an instance, intuitive rendering software products often offer high Flexibility in customising material/environment/camera settings for 3D CAD models. They enable the low Use Cost of CAD in this tool-use condition in the later design phases, especially when the final design is confirmed and photorealistic level of rendering (regarding the material, lighting and environment) is required as industry-standard deliverable.

In the Early-Middle phases, the sentiment analysis of the interview data also shows that, in *external communication*, Digital Sketching has won the favour (more positive sentiment ratings) of the designers on both Level of Aesthetics and Use Cost (see Figure 5.17). As the study suggests, having benefited from its Flexibility in certain design visualisation aspects (e.g. modifying or changing forms, adding shades and textures), Digital Sketching is considered by the designers as a time-efficient tool in *external communication* in industrial design practice for generating a preferable and satisfying Level of Aesthetics for the clients and other non-designer stakeholders.

• User Expertise and User Loyalty

Apart from the key DTCs, User Loyalty and User Expertise were mentioned by interview participants as they may have influences on the time efficiency of the use of Digital Sketching. These two characteristics were also proposed in the diagram of extended key Design Tool Characteristics (DTCs) in *external communication* in Chapter 5, Subsection 5.10.2. Table 7.3 lists four interview participants, who are frequent users of Digital Sketching in this tool-use condition, and who have shown strong positive sentiments on their User Loyalty towards Digital Sketching. For example, "I will do Digital Sketching [to communicate with clients] and I love doing it", and "a Photoshop interpretation of a rendered image is my preferred deliverable to a client". However, these positive sentiments of User Loyalty to Digital Sketching may lead to low time efficiency in the Early-Middle phases if not used with appropriate awareness and control of the visualisation activities. In other words, the immersive experience of creating representations with Digital Sketching for *external communication* could be time-consuming and redundant in the Early-Middle phases.

Polished Digital Sketching examples on the internet or at the workplaces done by experts may give the designers with lower User Expertise an inappropriate impression of Digital Sketching. In *external communication*, the low time efficiency of Digital Sketching could be associated with high Expectation of the resulting design representations. A few interview participants with low User Expertise on Digital Sketching had similar feelings (see Table 7.3). Three interview participants with low User Expertise on Digital Sketching have mentioned this characteristic in *external communication*, and all of them expressed negative sentiments towards the tool's time efficiency. These designers tend to either completely give up learning Digital Sketching after initial attempts because they can rely on the Digital Sketching experts in their group to do "those high-level sketches", or they will choose an alternative tool if there are no Digital Sketching experts in their group; e.g., "we need to do something a bit more polished, and our only option at the moment was to do a CAD model". In Table 5.3, the number of interview participants that have tried the tool but stopped is higher in Digital Sketching than in its

neighbouring tools. It indicates that at an early point of building up their User Expertise, designers already gave up on learning Digital Sketching.

DTCs \ References (Participants)	Total	Positive	Negative	Mixed
User Loyalty	4	4	0	0
User Expertise	3	0	3	0

Table 7.3 Expertise and User Loyalty of Digital Sketching in External Communication Mentioned in the Interview Study

In the interviews, the sentiment results of User Expertise and User Loyalty of Digital Sketching from the designers were quite opposite to each other, which may have negative influences on the perceived time efficiency of this tool in *external communication*. Designers with high User Expertise of Digital Sketching could easily develop high User Loyalty towards the tool and vice versa. It can make Digital Sketching a quick and fast tool for them to use in this tool-use condition. These designers also tend to have a more appropriate Expectation on the resulting digital sketches that communicate the design works to clients and other stakeholders.

However, the literature and experiment results also indicate that there is a risk for high User Expertise designers to become immersed in creating overly polished digital sketches, especially when the resulting representations are intended to be used in *external communication*. Hence, the high User Expertise could also damage the time efficiency in this tool-use condition if used in a careless way. Also, overly polished digital sketches from skilled peers or the internet may inhibit the beginner level designers' willingness to develop their User Expertise of Digital Sketching and misguide their perception of the time efficiency of using it in *external communication*.

▼ Effectiveness of Using Digital Sketching in External Communication

Interview results show that the usage of Digital Sketching in *external communication* is higher than in other tool-use conditions, which could be related to its use in creating effective representations for clients. Some shared key DTCs across the three tools in this tool-use condition (see Section 5.9.2) explain this phenomenon. Based on the associations between them, relevant key DTCs are grouped into 2 sets for discussion on the use of Digital Sketching in achieving effective design representations in *external communication*. The two groups are 1) Level of Commitment, Ambiguity and Level of Detail, and 2) Level of Aesthetics and Expectation, which are now discussed below.

• Level of Commitment, Ambiguity and Level of Detail

According to the experiment results (see Chapters 5 and 6), industrial designers usually don't feel very confident about only using "rough" traditional sketches to convince stakeholders to buy-in to their ideas. A comparison of the Level of Commitment across the three tools is figuratively illustrated in Figure 7.6. The perceived low Level of Commitment from the clients with traditional sketches could be related to the Ambiguity and Level of Detail of Traditional Sketching. The study suggests Traditional Sketching during the Early-Middle phases is usually high in Ambiguity and low in Level of Detail, which is effective for externalising ideas but not necessarily effective for *external communication*. In other words, the usually ambiguous traditional sketches with low levels of detail could inhibit the extent clients would commit with the proposed design solutions.

The observation results indicate that Ambiguity and Level of Detail are associated with each other to a degree in *external communication*. As the design solutions keep developing along the design process, the Level of Detail desired by the designers in *external communication* gets harder to convey by only using Traditional Sketching – even in the Early-Middle phases. In general, traditional sketches have higher Ambiguity and lower Level of Detail, which could cause client confusion and misinterpretations of the design concepts. If the communication becomes too disruptive because of the misinterpretations, clients may feel less attached to the concepts, and hence show a low Level of Commitment. If the misinterpretations turn out to be more negative, designers could be risking their business with this tool.

Therefore, the study results suggest that the combination offered by Traditional Sketching regarding Level of Commitment, Level of Detail and Ambiguity may not be preferable for generating effective design representations in formal *external communication*, especially in the modern context.

On the opposite side, the study results show that the Ambiguity of CAD is too low in *external communication* for the Early-Middle phases. Clients may mistake the potential design concepts as more finalised design solutions when they see CAD renderings with realistic lighting and materials. The lack of Ambiguity in the design representations generated by CAD may also make clients feel less in control of the project directions. The negative consequences of presenting realistic-looking CAD renderings in the Early-Middle design phases may include (but are not limited to) the following: 1) clients get less involved with the design development; 2) clients have higher Emotional Commitment to a premature concept that can inhibit the design development; and 3) clients terminate the project due to disagreement with the concepts thinking it's not open to debate anymore, or clients terminate the project earlier than expected thinking it is finished.

Moreover, the study also shows that the representations generated in *external communication* using CAD are also not very effective from the designers' perspective. For example, appropriate CAD models require a high Level of Detail as support to build, which is not ideal for freedom of thinking in the earlier design phases. Forcing a high Level of Detail on a premature design concept may lead to the final failure of a design project. If designers choose CAD renderings as the design representations in *external communication*, their behaviour could be perceived as showing a high Level of Commitment to the concepts, which may not be what they want. Hence some miscommunication could be foreseen.

Compared to Traditional Sketching and CAD, interview results (see Subsection 5.5.1) indicate that Digital Sketching may offer a better combination regarding these key DTCs in *external communication* during the Early-Middle phases in industrial design practice. Compared to CAD, Digital Sketching seems to have a relatively higher level of Ambiguity due to its nature of being a sketching tool. Digital Sketching could also generate suitable Levels of Commitment for both designers and clients, which also meet the objectives of the design phases. It could reserve space for designers so they can keep developing and refining the design in later phases in the design process.

Compared to Traditional Sketching, interview participants suggested that Digital Sketching could provide a relatively lower level of Ambiguity and a higher Level of Detail that make the design concepts less abstract for clients or non-designer stakeholders. With a better understanding of the design concepts, they may also generate a more appropriate Level of Commitment, based on the digital sketches, to keep the design project on track and give constructive feedback. As illustrated in Figure 7.6, Digital Sketching offers preferable ranges of both Level of Commitment and Ambiguity: 1) for designers to effectively convey the design concepts and reserve design freedom in *external communication*, and 2) for non-designer clients and stakeholders to effectively get involved with the design process and give feedback.

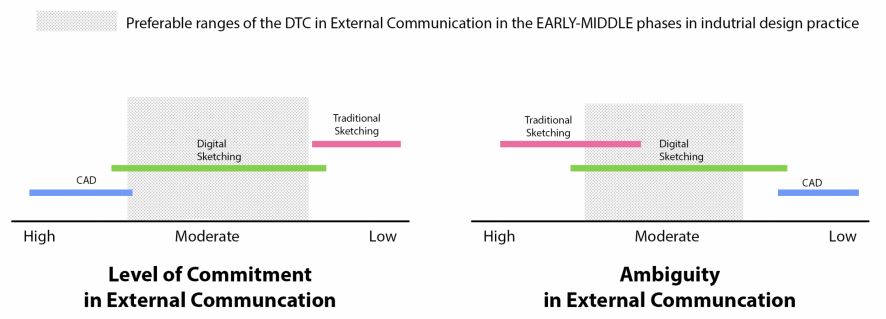


Fig. 7.6 Figurative Illustration: Preferable Level of Commitment and Ambiguity in External Communication in the Early-Middle Design Phases

• Level of Aesthetics and Expectation

The study suggests that Digital Sketching could offer an effective and achievable Level of Aesthetics for the design representations/visualisations, which aligns with designers' general Expectation in this tool-use condition. As presented in the interview results (see Subsection 5.5.2), Digital sketching has a moderate Level of Aesthetics in *external communication* in the targeted design phases. The Level of Aesthetics supported by Digital Sketching is perceived by the practising designers as effective in terms of "neat", "nice" and "more consistent". In Section 5.9.2, sentiment results of Digital Sketching on the Level of Aesthetics in this tool-use condition is the most positive across the three tools that are investigated in this study. In other words, when using Digital Sketching, the Expectation of the resulting design representations is generally achievable.

Specifically, in this tool-use condition, the Expectation of Digital Sketching (mostly on the Level of Aesthetics to be achieved) and the resulting representations are well aligned. This match ensures the effectiveness of the tool as well as its perceived effectiveness among the tool users. It could be partly due to the level of Expectation introduced to the designers in formal education and that they have been applying it as "common sense" in practice. For example, Digital Sketching was mostly introduced for beautifying design works in previous industrial design education. Both literature and interview results concur with this current use of Digital Sketching for "polishing up" traditional sketches. So, the Expectation of using Digital Sketching for achieving a moderate Level of Aesthetics in *external communication* is a norm for the majority of industrial designers; consequently, the resulting design representations are usually effective. More discussions on the relationship between experience in formal education and tool-use behaviours in practice are given in Section 7.4.

The moderate Level of Aesthetics of Digital Sketching is also supported by the moderate Level of Detail, especially the Aesthetic Detail (see Subsection 5.5.2). In general, the study suggests that using Digital Sketching in *external communication* during the Early-Middle phases could help to meet the Expectation of designers on Level of Aesthetics and convey the design concepts with a preferable Level of Aesthetics for clients.

▲ Summary: The Manifestation of Digital Sketching in External Communication

The study suggests that the time efficiency of using Digital Sketching in *external communication* could be better than both Traditional Sketching and CAD in the Early-Middle phases in industrial design practice. Reasons behind this pattern of use include, but are not limited to, the high Flexibility offered by Digital Sketching; hence, a low Use Cost in creating design representations with suitable (medium to high) Levels of

Aesthetics for both designers and clients. The User Loyalty and User Expertise of Digital Sketching are critical for designers to actually save time with this tool. The study indicates that having appropriate Expectations on the resulting design representations is important for controlling the time spent on the design visualisations. It is also critical for designers with low User Expertise to gradually develop their skills and User Loyalty, thus gaining benefits in this tool-use condition.

Digital Sketching is relatively well accepted in *external communication* for achieving effective design representations for clients and other stakeholders. Relevant DTCs could contribute to this specific pattern of its use during the Early-Middle phases in industrial design practice; namely, moderate Level of Commitment, Ambiguity, Level of Detail and Level of Aesthetics. Compared to Traditional Sketching, Digital Sketching offers a higher Level of Commitment and Level of Aesthetics to secure the clients/business. It also offers a lower level of Ambiguity with a relatively higher Level of Detail to convey the concepts to clients. Compared to CAD, Digital Sketching offers a lower Level of Commitment and Level of Aesthetics to not "over-claim" the design progress and mislead stakeholders' perceptions of the project. For both designers and other stakeholders, Digital Sketching could offer a higher level of Ambiguity to reserve design space for the later design phases. Findings on the impact from designers' Expectation on the tool use behaviours further explain why the use of Digital Sketching can facilitate effective design visualisations in *external communication*.

7.2.3 Patterns of Use of Digital Sketching for Internal Communication

According to the interview results in Subsection 5.9.3, the interview data collected regarding the manifestation of design visualisation tools in *internal communication* are substantially less than the other tool-use conditions. It indicates that the selection and use of visualisation tools in this tool-use condition may not be a major concern for most of the designers.

In the interviews, Traditional Sketching was considered as the primary tool in *internal communication* with positive sentiment associations. The study results concur with the literature review (see Chapter 2), which indicate that Digital Sketching is not well-adopted or accepted by designers in *internal communication*. The study suggests that the current use and user experience of Digital Sketching in this tool-use condition is lower than in both Traditional Sketching and CAD. To understand the phenomenon, the patterns of use of the three tools in *internal communication* are discussed with some highlighted DTCs based on the experiment results.

However, the discussion is not as thorough as is in the other tool-use conditions due to the limited data. It is conducted with the same perspectives; namely, time efficiency and resulting effectiveness. Within the scope of the Early-Middle phases in the industrial design process, discussion of the manifestation of Digital Sketching in *internal communication* is given as follows.

▼ Time Efficiency of Using Digital Sketching in Internal Communication

The study results suggest the time efficiency of using Digital Sketching in *internal communication* currently does not appear satisfying for designers. At the same time, time efficiency is critical in this tool-use condition since it would be economically beneficial to have quick iterations between generating design representations and receiving peer feedback. Among the frequently mentioned DTCs, Mobility of a tool/resulting representation, as well as the User Accessibility to a tool, are considered the most relevant characteristics to the time efficiency of the design activities in *internal communication*. The discussion is developed accordingly.

• Mobility and User Accessibility

In general, *internal communication* conducted in the Early-Middle phases is to convey the design ideas to other designers or engineers in the team and receive their feedback. Interview results suggest designers would expect a quick and flexible turnaround in this tool-use condition so they can go back to design activities for either *externalisation* or *external communication*.

Investigated designers indicated that the ideal scenario is they can quickly show the design representations to "someone on the other end of the room [the design studio]", or during a team meeting, and seek their opinions on the design concepts. The study suggests that the Mobility and User Accessibility of a design visualisation tool could have strong impacts on the time-efficiency in this tool-use condition.

Digital Sketching and CAD are considered slower than Traditional Sketching to work in this condition by many designers. As digital design visualisation tools, Digital Sketching and CAD need to run with software programs on a digital platform, which usually requires an electronic device. In general, the digital devices for Digital Sketching and CAD are not as mobile or accessible as a cheap sketchpad for Traditional Sketching. This lack of Mobility or User Accessibility could damage the time-efficiency to a certain degree.

On one side, carrying a sketchbook to show design concepts to other team members at work is considered the fastest by many of the interview participants. On the other side,

professional digital devices for Digital Sketching are not always mobile and sometimes not provided at the workplace. Hence, due to its lower Mobility and User Accessibility, the use of Digital Sketching is not comparable to the dominant use of Traditional Sketching in *internal communication*. Compared to CAD, which shares a similar level of limitation on Mobility with Digital Sketching, Digital Sketching also has a lower User Accessibility. This is because – unlike Digital Sketching – no special or extra device is needed to run CAD programs apart from standard computers or laptops.

Fortunately, the use of Digital Sketching in *internal communication* could be more and more efficient since the Mobility and User Accessibility of it have been improving over time. New technology enables improvement of the Mobility of Digital Sketching. The digital platform also ensures the high Mobility of the resulting digital sketches. For the Mobility of Digital Sketching devices, the weights and sizes of digital tablets are offered in a promising range of diversity. For example, based on an online report (Price, 2020), the current available sizes of an iPad that can support Digital Sketching are 7.9 (iPad mini), 10.2 (iPad), 10.5 (iPad Air), 11 (Pro) or 12.9 (other Pro). For the Mobility of resulting digital sketches at workplaces, servers and software products for sharing files (e.g. Slack and Microsoft Team) are also becoming more available for designers at workplaces.

Hence, carrying a Digital Sketching device or sharing a digital sketch to team members in industrial design practice is becoming easier and faster. The User Accessibility of Digital Sketching could also increase in the industry since prices of the professional digital sketching tablets are continuously more affordable. For example, there is a wide range of digital sketching tablets at reasonable prices to choose from for a working designer – or even a student. According to an investigation of Amazon.com (2020), drawing tablets with a display screen are around 500 Australian dollars and without a built-in screen are usually under 100 Australian dollars. Besides, Digital Sketching software programs are also available on many smart devices, e.g. iPad and Surface Pro, so there will be no extra compulsory investment on the device.

▼ Effectiveness of Using Digital Sketching in Internal Communication

The study results suggest that the results of using Digital Sketching in *internal communication* are not considered to be very effective by the participating designers. As discussed, the interview data of Digital Sketching in this tool-use condition are less than in other tool-use conditions. DTCs of Traditional Sketching (the dominant tool in *internal communication*) and CAD can help to explain what concerns and motivates designers to use a design visualisation tool in this tool-use condition. From this, the patterns of use of Digital Sketching can be explored to ensure its effectiveness.

The DTCs highlighted across the three tools in this tool-use condition include:

Fidelity, Level of Detail and Ambiguity: whether designers can effectively convey their mental image to other team members or not, and
Problem Re-framing: whether the design representations can stimulate new perspectives in viewing the design problem or not, and
Flexibility and Vertical Transformation: whether the tool can assist designers to modify and develop the design easily during team meetings or in team conversations or not.

Further discussions are as follows.

• Fidelity

Similar to the literature review results, the interview results suggest that effectively conveying mental images of design ideas to other team members is one of the designers' major concerns in *internal communication*. Fidelity – how well the design representations match the mental images – is considered as one of the key DTCs that dominate the tool-use patterns in *internal communication*. The interview results show that designers are positive about the low Fidelity offered by Traditional Sketching, especially in the Early-Middle phases. This is because even though the Fidelity of the traditional sketches is generally low, the required Fidelity of the mental images for designers to work with in Traditional Sketching is also low. In other words, designers do not feel the urge to have a clear mental image when using Traditional Sketching, so they can keep ideating freely.

Since the required Fidelity of Digital Sketching is usually considered higher than Traditional Sketching, it could be one of the factors that discourage designers to adopt Digital Sketching in *internal communication*. Even though the resulting Fidelity of the representations could be higher in Digital Sketching, the initial requirement on high Fidelity for mental images could stress designers in this tool-use condition. Hence, the Fidelity of Digital Sketching could be one of the aspects to consider, test, and perhaps be improved by design tool developers to boost the effectiveness of this tool.

However, based on experiment results in other tool-use conditions, the required Fidelity of Digital Sketching is not necessarily always higher than Traditional Sketching. This requirement could be more like a stereotypical impression or understanding of Digital Sketching. For Digital Sketching to give more effective design representations in *internal communication*, it is essential to make designers aware that it is also possible to maintain low Fidelity requirements on the mental images when using this tool.

• Level of Detail and Ambiguity

Level of Detail and Ambiguity of CAD are mentioned as positive and contributing characteristics in *internal communication* in the interviews. When conveying the design concepts to other team members, the Level of Detail offered by CAD, especially the 3D scale and other engineering details, can help to reduce the unwanted Ambiguity in the middle design phase. Even though the Aesthetic Detail of these earlier CAD models can hardly match the designer's mental image (as it is time-consuming to do so in CAD), CAD is used in certain scenarios for clarifications on Engineering Detail in *internal communication*. In other words, CAD offers high levels of Engineering Detail but potentially low levels of Aesthetic Detail in the Early-Middle phases in this tool-use condition.

Digital Sketching, as a digital sketching tool, has the capability of ensuring a higher level of Engineering Detail than Traditional Sketching by enabling numeric controls and inputs. At the same time, it may also help to achieve a good level of Aesthetics Detail.

As the interview results suggest, it would be ideal to facilitate a good level of Aesthetic Detail in the earlier phases and also be able to provide the needed Engineering Detail when the *internal communication* progresses from the early phase to the middle phase. Using Digital Sketching to communicate design concepts within the design team could provide a balance between the Engineering Detail and Aesthetics Detail – hence, appropriate Ambiguity – especially in the Middle phase of the industrial design process.

• Flexibility, Problem Re-framing and Vertical Transformation

In *internal communication*, receiving feedback and working collaboratively on design concepts are as important as conveying them to others, which is slightly different from the *external communication* condition. The interview results suggest good Flexibility can assist Problem Re-framing and Vertical Transformation, and hence facilitate effective collaborations in *internal communication*. It is one of the critical reasons for Traditional Sketching to be successful as a dominant tool in this tool-use condition.

Compared to Traditional Sketching, interview participants suggest Digital Sketching and CAD tools are not as flexible for designers to work "side by side" simultaneously at the same desk or platform. Flexibility to use the design visualisation tools for making amendments on the design concepts while having continuous conversations is important to stimulate opportunities for Problem Re-framing and Vertical Transformation in the Early-Middle phases. Since Digital Sketching hardware usually can only be operated by one person at one time, it is considered not very flexible by the interview participants.

However, with the development of technologies, the digital platform of Digital Sketch-

ing also opens up new online collaboration opportunities. More and more CAD software products enable people to build on the same CAD file from different computers simultaneously. The study suggests a similar feature in Digital Sketching would benefit its effectiveness in both *internal* and *external communication*. Since people can have real-time online conversations, irrespective of their physical distances, it could be very effective in both local and international collaborations. The advantage of building upon a digital platform would further benefit Digital Sketching in achieving effective results in *internal communication*, especially in the contemporary diverse setups at workplaces. Digital Sketching can support remote collaborations. For example, during the recent COVID-19 pandemic, designers working from home, or collaborating when other members are physically far away, could have really benefited from online collaborative *internal communication*.

It seems that Digital Sketching could be supportive in achieving effective results in this tool-use condition. It may be not as flexible as Traditional Sketching at the moment, but its Flexibility in supporting Vertical Transformation could still be relatively higher than CAD. Hence, it can stimulate more design iterations during the *internal communication* and facilitate online long-distance collaborations.

▲ Summary: The Manifestation of Digital Sketching in Internal Communication

The study results suggest that using Digital Sketching in *internal communication* is currently considered time consuming and inefficient compared to Traditional Sketching and even CAD. Mobility and User Accessibility of the tool are part of the major concerns in this tool-use condition. However, the development of new technologies in relevant areas could make Digital Sketching devices and the resulting design representations more and more mobile and accessible in practice. It would eventually help to reduce the time cost of using Digital Sketching in this tool-use condition.

The study suggests that the outcome of using Digital Sketching in *internal communication* is also not considered as effective as Traditional Sketching. However, there are some characteristics of this tool that may have the potential to further support in-team communication during the design process. To be used and applied in this tool-use condition, characteristics of Digital Sketching that need noting are 1) not requiring high Fidelity on the mental images from designers so they can use it with less risk of becoming fixated on certain ideas; 2) improving the awareness of Digital Sketching being a Sketching tool that can be used to make quick design transformations; 3) offering a good balance between Level of Detail and Ambiguity that could benefit in-team communication in the Middle phase; and 4) adopting new technologies to further improve Flexibility for enabling further online and offline collaborations. Online real-time collaboration

is a potential direction where Digital Sketching can exceed Traditional Sketching in *internal communication* because of the rapid globalisation and virtualisation of our contemporary workplaces. All in all, increased usage and applications of Digital Sketching in *internal communication* can be expected in the future.

7.2.4 How Digital Sketching Manifests and the Significance of Understanding It

This subsection focuses on answering research question 2; namely, "how does Digital Sketching manifest in the Early-Middle phases in industrial design practice?" In this study, the manifestation of Digital Sketching is defined as the patterns of use and applications of the tool in practice. Discussion is developed based on the tool-use conditions from the time efficiency and effectiveness perspectives. The answer is further summarised based on the summaries above, which highlight and explain the patterns of use of Digital Sketching in industrial design practice. The literature review and the interview and observation results together triangulated the explanations based on the tools' key Design Tool Characteristics (DTCs).

How Digital Sketching Manifests in the Early-Middle Phases

Briefly, designers are more positive about the use of Digital Sketching in *external communication* than in other tool-use conditions, which concurs with its current use in practice – a beautifying tool in the middle phase. Designers are more familiar with using Digital Sketching to communicate design concepts with clients or other stakeholders. This pattern of use of Digital Sketching had been introduced during designers' formal education decades ago. Apart from the familiarity of relevant skills, digital features of this tool also make the modification of design concepts fast and easy compared to traditional media-based tools. It is flexible, hence this pattern of use could also be chosen for saving time. Encouraging younger generations to keep studying this tool and improve their expertise is likely to further facilitate this application of the tool.

During the Early-Middle phases, using digital sketches to communicate with clients could give an appropriate impression of the design concepts. It is neither too polished to be mistaken as finished work nor too rough to show the designer's profession. The moderate combination of levels of detail and realism, space for information, discussion and imagination make the tool a success in *external communication*. A more comprehensive understanding of the manifestation of Digital Sketching in this tool-use condition would help designers to further exploit it in design practice for gaining better communication experiences with clients and other non-designer stakeholders.

However, in *externalisation*, the study results suggest the patterns of use and applications of Digital Sketching will be more diverse than its current use in the Early-Middle phases. Digital Sketching itself is not necessarily a tool that can inhibit design creativity in the early phases if it is used with a clear design purpose. On the contrary, Digital Sketching shows its use in assisting design ideation and development in this study.

As discussed above, the lack of Digital Sketching expertise, or no access to the devices, can contribute to this lack of use. Designers are also more familiar and happier to use the tools that they already know. A new tool, Digital Sketching, can make the design activities become time-consuming. However, if the time and skill factors are not a problem, then the use of Digital Sketching in *externalisation* could be flexible for generating new concepts, modifying existing concepts, receiving space for further development and introducing accurate dimensions to the design representations. To save time and gain these potential benefits, creative patterns of use and applications of Digital Sketching in *externalisation* could be made based on the key DTCs and should be encouraged among designers and future designers.

The use of Digital Sketching in *internal communication* is perceived as possibly time-consuming and ineffective to meet the requirements of this tool-use condition. The dominant tool, Traditional Sketching, and its key DTCs in this tool-use condition, guided the discussion on how to modify the use and applications of Digital Sketching accordingly.

The development of new technologies in relevant fields also suggests many promising solutions in improving the time efficiency of Digital Sketching in *internal communication* by making the devices cheaper and more portable. Online real-time collaborations enabled by digital design tools could boost the use of Digital Sketching for long-distance and international *internal communication*. An up-to-date understanding of Digital Sketching is also suggested as important to erode some of the stereotypical impressions of the tool that are limiting its creative uses. For example, in this tool-use condition, Digital Sketching is considered to need a foundation design concept to work with, which may discourage the use of it in quick turnaround in-team communications and iterations. Design tool developers should push Digital Sketching to offer a flexible, clear and collaborative user experience in this tool-use condition. The designers barely use or consider it in *internal communication*, and future investigations are needed to discover the ideal patterns for its use.

Significance of Understanding the Manifestation of Digital Sketching

With the DTCs framework, the study forms an up-to-date understanding of how Digital

Sketching manifests during the Early-Middle phases in the industrial design process, and why. It helps to clarify what motivates and concerns practising designers to use (or not use) Digital Sketching in different tool-use conditions during the Early-Middle phases in their daily industrial design practice. It is important to be comprehensive and specific when it comes to understanding how a design visualisation tool manifests. The understanding of Digital Sketching needs to be comprehensive so the majority of the influencing factors (DTCs) can be discovered. The understanding of the use of Digital Sketching also needs to be specific so it can be used to guide or work for multiple parties in real-world design projects.

With the DTCs framework, the study forms a more up-to-date understanding of how Digital Sketching manifests during the Early-Middle phases in the industrial design process. It helps to clarify and explain what motivates and concerns the designers to use (or not to use) Digital Sketching in different tool-use conditions during the Early-Middle phases in practice.

It is important to be both comprehensive and specific when it comes to understanding how a design visualisation tool manifests in practice. On one hand, the understanding of Digital Sketching needs to be comprehensive so that the majority of the influencing factors (the DTCs) can be revealed for more holistic management of its use in practice. On the other hand, the understanding of the use of Digital Sketching also needs to be specific; hence, its strengths and barriers can be flagged. Together, this extensive understanding of the way Digital Sketching manifests in practice leads to the following significance .

- **For Researchers**
  Understanding the current manifestation of Digital Sketching could open up more research opportunities for the tool. Especially in *internal communication*, identified motivations and concerns could be further investigated to deepen the domain knowledge. The discovered patterns of use and applications of Digital Sketching could work as a reference for conducting comparisons of Digital Sketching with other emerging tools in the field.

- **For Design Tool Developers**
  The discovered patterns of use and applications of Digital Sketching could work as a stepping stone for the continuous development of the tool. It highlights the pains and gains of their target users; hence, the development can be conducted accordingly to offer better user experience.

- **For Design Students/Designers**
  Designers and design students can learn from how Digital Sketching manifests

in practice and customise when and how to use it accordingly. A better understanding of the tool is the foundation to exploit it for achieving effective design results in a timely manner, and hence empower designers to be more productive in practice.

- **For Design Educators**
  To ensure the success of our future designers, design educators need to cope with the fast development of technology and tools in the industrial design field. To deliver high-quality teaching content of Digital Sketching, an up-to-date understanding of it is essential. This study answers how Digital Sketching manifests in practice, which could help design educators to further develop their curriculum involved with Digital Sketching so the possibilities and resources offered by the tool won't get wasted. For example, the outdated stereotypical use of Digital Sketching may be altered from when this tool is introduced into education.

Moreover, the comparisons across the three tools again highlighted some of the bipolarised differences between Traditional Sketching and CAD, which further explains the troublesome transitions between them. This could open up opportunities for Digital Sketching to be used to ease said transitions. In the following section, the comparisons form the basis to answer research question 3; namely, whether Digital Sketching could be a "pathway" to ease these troublesome transitions or not.

7.3 Digital Sketching: A "Pathway" to Ease the Transitions Between Traditional Sketching and CAD?

From literature, as discussed in Chapters 1 and 2, Traditional Sketching and CAD show bipolarised design tool characteristics in industrial design, which could cause troublesome transitions between them. Both are commonly used as neighbouring tools in the Early-Middle design phases in practice; hence, these transitions present an opportunity to improve designers' experience and practice. For clarity, it should be noted that discussion within this section is all in the scope of the Early-Middle phases of the industrial design process, unless stated explicitly.

This section begins by further explaining the troublesome transitions in terms of the Design Tool Characteristics (DTCs) of these two tools. The study results are now discussed in terms of levels of support for the DTCs offered by the tools rather than the level of DTCs offered by the tools. The difference here is the level of a characteristic of a tool can be low, but it may be considered as a high level of support for the designers.

For example, the Use Cost of Traditional Sketching is generally low, which offers a high level of support for designers to use it in the Early-Middle phases.

Then, the potential for Digital Sketching to ease the transitions is discussed based on the levels of support for the relevant DTCs of Digital Sketching. Effectiveness and time efficiency of Digital Sketching under each design tool-use condition are also compared to its neighbouring tools for arguing whether it could be a transitional tool or not.

It is worth noting that the study results suggest that the answer to research question 3 cannot be simplified to a simple "yes" or "no", due to the complexity of different tool-use conditions and design phases; namely, when and where the transition happens. Hence, opportunities (strengths) and barriers surrounding the use of Digital Sketching under each design tool-use condition are discussed separately for estimating the possibility of Digital Sketching being a transitional tool.

7.3.1 Opportunities for Digital Sketching to Ease the Transitions

As mentioned above, the understanding of how Digital Sketching manifests in practice compared to Traditional Sketching and CAD is used as the basis to discuss the answer to research question 3. First, the polarised differences between the key Design Tool Characteristics (DTCs) of Traditional Sketching and CAD in each tool-use condition are flagged to explain the existing troublesome transitions. In comparison, the prominent strengths of Digital Sketching are then identified focusing on its wide range and moderate levels of support for these most frequently cited DTCs. Then it is argued whether Digital Sketching offers a "pathway" between its more polarised neighbouring tools.

To be specific, as discussed in Chapters 1 and 2, Digital Sketching has inherited some positive affordances from both sketching and digital media/platforms for conducting timely, efficient design processes and achieving effective design representations. At the same time, literature shows the transitions between its neighbouring tools during the design process could be troublesome. The theoretical potential of using Digital Sketching to ease these troublesome transitions is proposed as part of the literature review results. Therefore, in addition to providing a more comprehensive understanding of Digital Sketching in practice, the experiment results are further used to specifically discuss this possibility of easing the troublesome transitions. In this subsection, the opportunities of using Digital Sketching to ease the transitions are explained with its levels of support on the relevant DTCs in each tool-use condition.

In *externalisation*, the study results suggest the manifestation of Digital Sketching in practice shows opportunities for using it to ease the transitions between Traditional Sketching and CAD. As is discussed in Chapters 2 and 5, there are a few troublesome transitions that can occur between Traditional Sketching and CAD in *externalisation* during the Early-Middle phases. These troublesome transitions are related to certain most frequently mentioned characteristics in this tool-use condition: **Flexibility, Use Cost, Level of Detail, Level of Aesthetics, Fidelity and Accuracy**. In Figure 7.7, these DTCs and the associations between them are highlighted for quick reference.

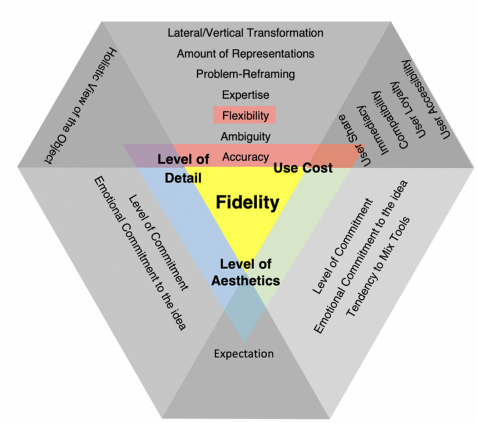


Fig. 7.7 Key DTCs Related to the Troublesome Transitions in Externalisation

According to the study results, these DTCs are where Traditional Sketching and CAD show the most polarised differences in *externalisation*, which can have a negative impact on the time efficiency and resulting effectiveness of the design process. The different levels of these characteristics in Traditional Sketching and CAD result in different levels of support for designers regarding these DTCs in this tool-use condition. Based on the levels of DTCs from the interview and observation results, the levels of support offered by Traditional Sketching and CAD are given according to the favourable DTCs in the Early-Middle phases in Subsection 3.3.2. To give a more intuitive overview of their bipolarised nature compared to each other, the different levels of support given by these two tools are figuratively illustrated with coded colours in Figure 7.8. From this, their differences are also stressed from a more holistic perspective of DTCs' associations enabled by the use of the DTCs framework (see Subsection 7.1.1). Compared to simply looking at each individual DTC, this collective perspective on their associations may give a richer understanding of the tools' nature.

The four DTCs forming the inner core of the association in *externalisation* are Level of Detail, Use Cost, Accuracy and Fidelity. The interview results suggest they are essential for understanding tools in this tool-use condition, and they are correlated with

each other. Positive correlations between Level of Detail and Use Cost, and Accuracy and Fidelity, are proposed based on the observation results. The differences between the tools on these DTCs and designers' attitudes towards them are revealed by the study results, which form the basis to discuss the possibility of Digital Sketching being a "pathway" to ease the transitions. Another two key DTCs from the interview results are included in the discussion due to their close associations with the above DTCs.

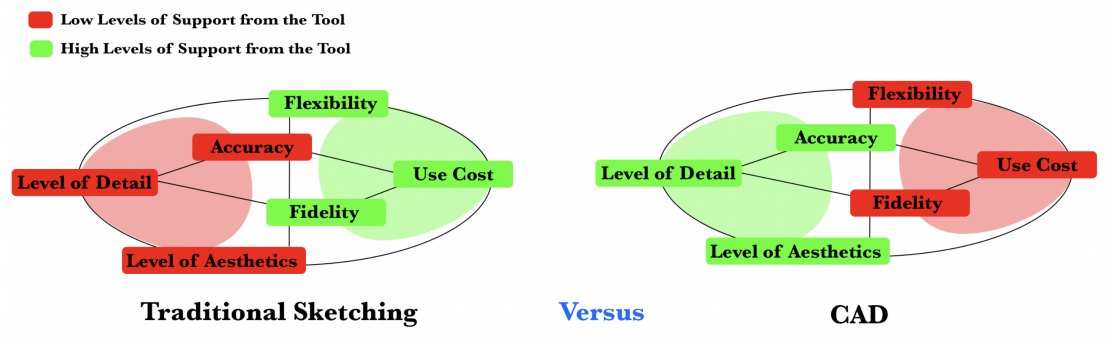


Fig. 7.8 Polarised Differences of Traditional Sketching and CAD on the Key DTCs (as an Association) in Externalisation

To be specific, the study results show it is difficult for Traditional Sketching and CAD to give high levels of support for both Accuracy and Flexibility at the same time. According to the interview results in Chapter 5, the low levels of Accuracy supported by Traditional Sketching could be one of the reasons that it has high levels of support for Flexibility. For example, no measuring or numeric inputs are required for good Accuracy in general when Traditional Sketching is used in *externalisation* in the Early-Middle phases for flexible, freehand ideation sketching. On the contrary, CAD has higher levels of support on Accuracy that could limit the operational Flexibility, and designers widely agree that CAD is a more rigid tool to use.

Similarly, the differences of Use Cost, Level of Detail, Fidelity and Level of Aesthetics between Traditional Sketching and CAD and the resulting different levels of support from the tools are difficult to ignore. For example, high levels of support for Fidelity is defined since low levels of Fidelity are required of designers' mental images of the design concept. In contrast, low levels of support for Accuracy means resulting design representations could be less accurate. The positive correlation between the levels of Accuracy and Fidelity across the tools can lead to a negative correlation between the levels of support for these two DTCs. Based on the study results in Chapters 5 and 6, high levels of support for Fidelity from Traditional Sketching could have an impact on its low levels of support for Accuracy, Level of Aesthetics and Level of Detail. However, high levels of support for Fidelity also requires less time invested in visualisation activities (high levels of support on Use Cost). In other words, Traditional Sketching

has been viewed as a very flexible and time-saving design visualisation tool requiring less prepared mental images in *externalisation*. It also tends to achieve a low Level of Detail and Level of Aesthetics, often without accurate dimensions and proportions in the resulting sketches.

On the other hand, CAD has higher levels of support for Level of Detail and Level of Aesthetics, which tends to require a clearer mental image to start working with. As mentioned above, Flexibility is, to some extent, sacrificed for better Accuracy in CAD. Hence, the study results suggest that CAD generally offers abundant Level of Detail and can achieve a photorealistic Level of Aesthetics with high Accuracy. However, this could lead to more operational time spent on visualisation activities (high Use Cost). Therefore, CAD is also known for its lack of Flexibility, high Use Cost, and requires a clearer mental image (Fidelity) of the design to start with.

As illustrated in Figure 7.8, the levels of support for these characteristics of Traditional Sketching and CAD are not very well balanced or distributed. According to the interview results in Chapter 5, designers have noted these sharp changes and shown their negative sentiments towards both two tools regarding certain associations between the DTCs in *externalisation*. Consequential patterns of use and applications of these two tools are also noticed in practice during the observation study in Chapter 6. For example, in Subsection 6.3.2, the observation results show more evidence of these existing differences between Traditional Sketching and CAD. During the Early-Middle phases, when transitioning back and forth between Traditional Sketching and CAD in *externalisation*, designers could experience sharp and challenging changes with respect to these DTCs.

Referring now to Digital Sketching, the support for these same DTCs tends to be more moderate as illustrated in Figure 7.9. The levels of support together indicate more balanced associations between the DTCs. Hence, it shows support of Digital Sketching being a "pathway" to ease the related troublesome transitions between its neighbouring tools. In other words, Digital Sketching shows strengths as a visualisation tool in smoothing the sharp changes of these characteristics when transferring from Traditional Sketching to CAD, especially in *externalisation*.

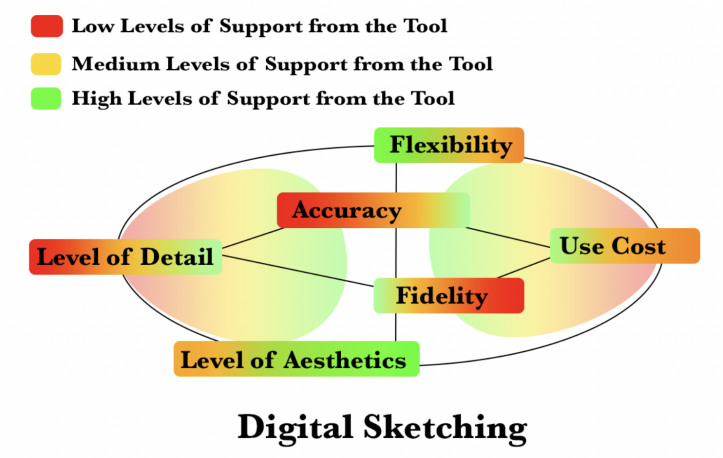


Fig. 7.9 Figurative Levels of Support From Digital Sketching on the Key DTCs (as an Association) in Externalisation

To be specific, the study results suggest that Digital Sketching, as a sketching-based stylus-input visualisation tool, has kept a moderate range of Flexibility as a Sketching tool and a medium range of Accuracy due to the digital platform. As elaborated in Subsection 7.2.1, its manifestation in this tool-use condition shows that Digital Sketching can be more accurate in dimensions and scales with numeric inputs enabled by the digital platform, which may slightly reduce the Flexibility but significantly boosts the Accuracy. Hence, the Use Cost of Digital Sketching could be marginally higher than Traditional Sketching but still lower than CAD in general for generating satisfying Accuracy and Level of Detail (both Aesthetic and Engineering Detail). Similarly, when conducting visualisation activities in *externalisation*, Digital Sketching may require a moderate level of Fidelity that depends on the expected Level of Detail, Accuracy and Level of Aesthetics to be achieved with the resulting design representations.

All in all, the study suggests Digital Sketching, via these DTCs, has the potential to bridge the differences between Traditional Sketching and CAD and thereby ease the troublesome transitions in *externalisation*.

In *external communication*, the study results align with the current trending use of Digital Sketching seen in practice, which it has adopted for certain transitional purposes in this tool-use condition. In this study, clearer and stronger support for Digital Sketching being a "pathway" to ease some troublesome transitions in *external communication* is revealed. Discussion is developed based on the levels of support for the identified essential Design Tool Characteristics (DTCs) of Digital Sketching and the comparisons conducted between the three tools. In Figure 7.10, these essential DTCs in *external communication* are highlighted, including **Ambiguity, Level of Detail, Level of Commitment, Flexibility, Use Cost and Level of Aesthetics**.

Similar to *externalisation*, polarised differences of these DTCs between Traditional Sketching and CAD are the potential causes of the troublesome transitions. The different levels of support for the essential DTCs are used to explain the existing transitions and discuss whether Digital Sketching could ease them.

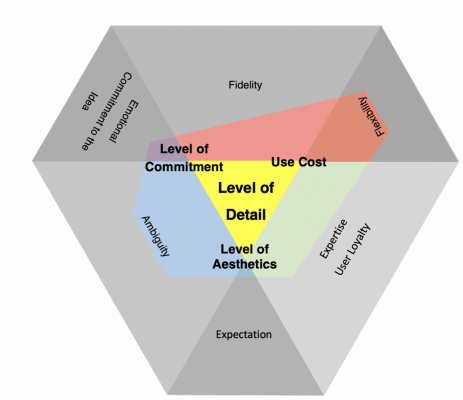


Fig. 7.10 Association of the Key DTCs Related to the Troublesome Transitions in External Communication

In the interview results (see Subsection 5.9.2), participants expressed their negative sentiments towards the differences in the mentioned DTCs between Traditional Sketching and CAD. It helps to explain the causes of some troublesome transitions that could affect the time efficiency and effectiveness in *external communication*. As discussed before, not only the DTCs of a design tool reflect its manifestation in practice, but also the associations between its DTCs draw a more multifaceted understanding of it (see Subsection 7.1.1). In Section 6.5, the associations between key DTCs of Digital sketching and its neighbouring tools are summarised based on the study results, from which the polarised levels of support for the essential DTCs between Traditional Sketching and CAD are noted.

In Figure 7.11, the different levels of support offered by Traditional Sketching and CAD for these most frequently mentioned DTCs and the suggested associations between them are figuratively illustrated. In this tool-use condition, Traditional Sketching tends to offer high levels of support for operational Flexibility and Ambiguity for more re-interpretations, which also usually require less time to work with. However, highly ambiguous design representations are suitable for keeping the creative juices flowing but may not be ideal for delivering the design to non-designer clients or stakeholders.

The study results also indicate that designers feel Traditional Sketching has low levels of support for Level of Detail and Level of Aesthetics. As a consequence, the highly ambiguous traditional sketches usually lack detail and visual appeal to arouse an appropriate Level of Commitment among the clients. It can lead to misinterpretations of the

design idea, or worse, project terminations.

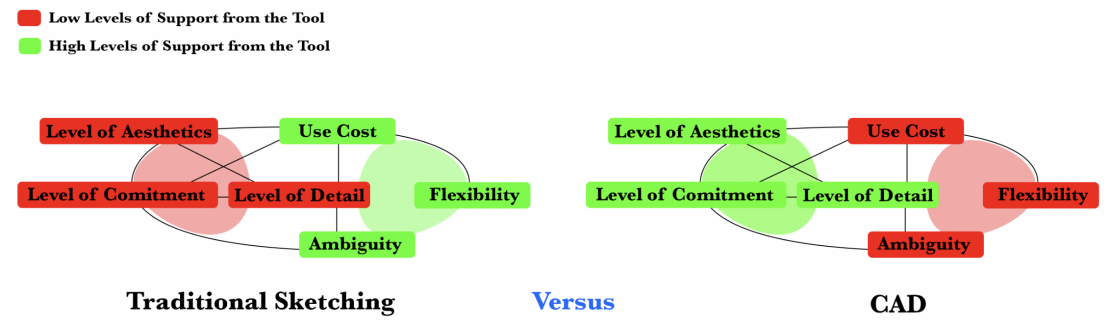


Fig. 7.11 Polarised Differences of Traditional Sketching and CAD on the Key DTCs (as an Association) in External Communication

On the contrary, CAD has high levels of support for Level of Detail and Level of Aesthetics, which can contribute to higher levels of support for generating a Level of Commitment that could be more favourable in *external communication*. As a consequence, CAD also shows low levels of support for Ambiguity that may leave less space for further design development, that could lock clients into a premature concept in the early phase. CAD is also more time-consuming, partially due to its lack of Flexibility, partly due to the higher levels of Detail and Aesthetics to be executed.

Hence, during the Early-Middle phases, when transferring from Traditional Sketching to CAD, the changes in the above DTCs could be too sharp to make an efficient and smooth transition in this tool-use condition. According to the study results, as is illustrated in Figure 7.12, Digital Sketching can offer preferable levels of supports for these characteristics that may ease the related transitions.

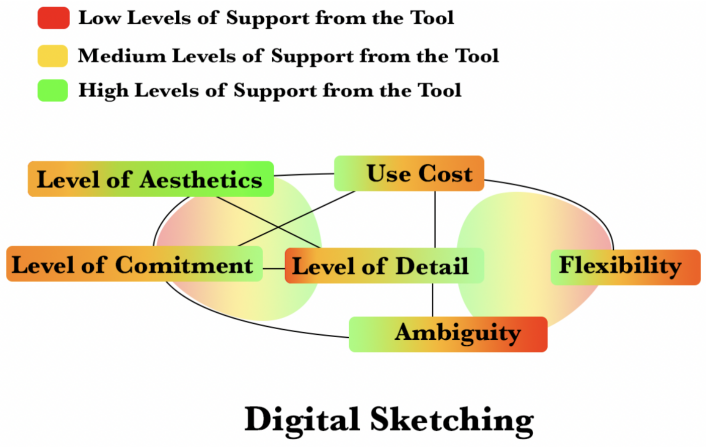


Fig. 7.12 Figurative Levels of Support from Digital Sketching on the Key DTCs (as an Association) in External Communication

To be specific, the observation results suggest Digital Sketching can offer a moderate

level of Flexibility, hence a medium Use Cost, when generating an appropriate Level of Aesthetics in *external communication*. Digital Sketching is presented as more flexible than CAD in terms of tool operation by interview participants and has even been considered more flexible than Traditional Sketching on undoing mistakes and applying colours/textures. Accordingly, it may offer an opportunity for designers to save time when visualising design ideas for clients and other non-designer stakeholders.

The decrease in Flexibility and Ambiguity when switching from Traditional Sketching to Digital Sketching, and later on in the process from Digital Sketching to CAD, is more gradual. It could potentially help to ease the designers into a more rigid platform and a clearer design direction during the Early-Middle phases in the industrial design process. More importantly, the moderate range of Ambiguity supported by Digital Sketching may meet the expectations of the target design phases, which are retaining appropriate space for designers to develop the design concepts further and for clients to give constructive feedback.

Similarly, the gradual increases of Level of Detail and Level of Aesthetics from Traditional Sketching to Digital Sketching, and then to CAD, could smoothly ease the designers into more fixed design directions. The wide range of Level of Aesthetics with an associated moderate Use Cost of Digital Sketching may help to bridge the extreme differences between Traditional Sketching and CAD in *external communication*.

Besides, the Level of Commitment generated by Digital Sketching during the target design phases could be in a suitable moderate range in that it is not rushing designers to narrow down their design directions to one, nor misleading clients to lock into a single specific design visualisation. Hence, Digital Sketching seems to be a promising "pathway" to ease the transitions between Traditional Sketching and CAD by providing moderate levels of support for these key DTCs in *external communication*.

In *internal communication*, the study results indicate that Digital Sketching has been little used in this tool-use condition compared to Traditional Sketching. In the interviews, designers mentioned the use of Traditional Sketching to communicate with team members in various scenarios. Traditional Sketching is considered as the primary tool for in-team communication during the Early-Middle phases in the industrial design process. As highlighted in Figure 7.13, the relevant essential DTCs for understanding the use of tools in this tool-use condition include, but are not limited to, **Flexibility and Use Cost** in generating the design representations, and the resulting **Level of Detail and Ambiguity**.

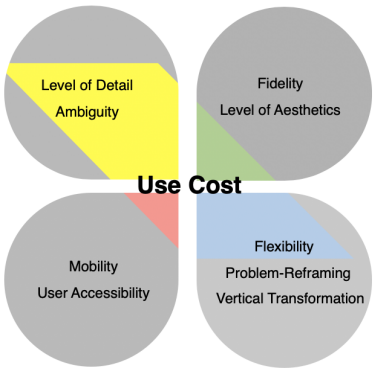


Fig. 7.13 Association of the Key DTCs Related to the Troublesome Transitions in Internal Communication

For a quick overview, Figure 7.14 figuratively illustrates the different levels of support offered by Traditional Sketching and CAD for these key DTCs in *internal communication* based on the study results.

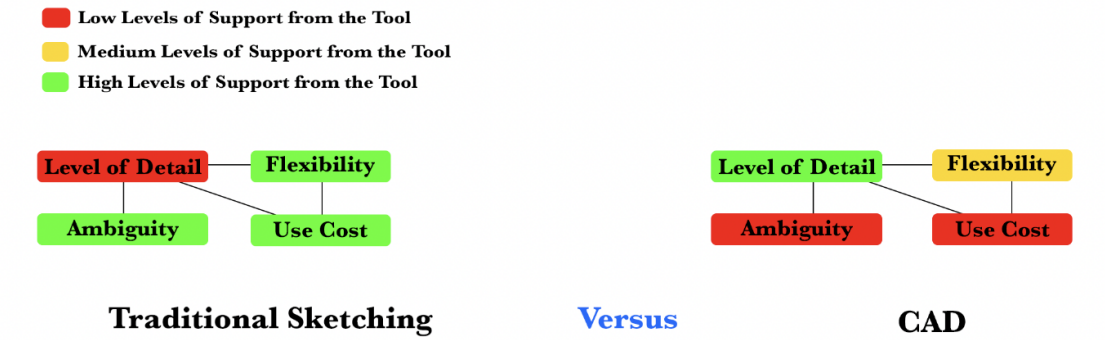


Fig. 7.14 Polarised Differences of Traditional Sketching and CAD on the Key DTCs (as an Association) in Internal Communication

In this tool-use condition, Traditional Sketching, as a tool, offers the opportunity for multiple people to make marks, changes and notes on the design representation within the same time frame, which is a flexible and low-cost approach. However, the nature of Traditional Sketching offers low levels of support for the Level of Detail and high levels of support for Ambiguity. According to the interviews, it could cause misinterpretations or unwanted reinterpretations in *internal communication*. It can become a more noticeable issue when the level of Engineering Detail climbs higher and higher in the middle design phase.

For example, if team members want to make dimensional changes quickly and have immediate visual feedback alongside their in-team communication, it could be challenging to achieve this with Traditional Sketching. The study suggests that designers enjoy the

flexible and fast uses of Traditional Sketching when communicating within their team. Still, the Ambiguity of traditional sketches could be a double-edged sword. It can help to stimulate creative juices in this tool-use condition, but it may also fail to achieve an appropriate Level of Detail for communicating design with more engineering-focused team members.

On the other hand, CAD models are generally less ambiguous with a high level of support for the Level of Detail. Still, CAD operations are time-consuming and lack Flexibility in making changes on Aesthetic Detail. Hence, CAD is also little utilised in this tool-use condition. For example, as interview participant 1 stated, "We print it [CAD model rendering] out, then we sketch on top of it" during internal team meetings to quickly and easily mark feedback on the CAD models. After this, it still takes time to make follow-up changes in CAD. The results also show that the use and applications of CAD in internal communication may increase as the project progresses. This is partially due to the Flexibility of CAD on making and viewing real-time changes of Engineering Detail in this tool-use condition, and the Flexibility of CAD is considered as moderate.

All in all, different levels of support for these DTCs are offered by Traditional Sketching and CAD. They have their advantages in different aspects of design in various design phases. Still, the polarised differences between them may also take designers' time and mental effort to switch from one to the other. Apart from their different levels of support for the DTCs, the troublesome transitions in *internal communication* could also relate to the switch between the working dimensions (2D/3D) and the platforms (Physical/Digital) of Traditional sketching and CAD. The study indicates that there could be some opportunities for Digital Sketching to ease these transitions between Traditional Sketching and CAD in *internal communication*. With limited direct data of Digital Sketching in this tool-use condition, the discussion below is based on the levels of support of Digital Sketching seen in other tool-use conditions and the author's expertise on this tool.

Figure 7.15 illustrates the levels of support for these DTCs that could be offered by Digital Sketching in *internal communication*. These levels of support are summarised based on the study results in other tool-use conditions, the author's experience as a digital sketch expert, and empirical observations at workplaces. As a 2D digital visualisation tool, Digital Sketching can offer moderate levels of support for Flexibility that may facilitate more efficient in-team communication in practice, especially with more and more cutting-edge technologies available in the field. Concerning Flexibility, modifications to Aesthetic Detail in Digital Sketching are generally considered as freer and less time-consuming than CAD. Digital Sketching also could be more flexible than Traditional Sketching when it comes to making changes to Engineering Detail alongside the

in-team communication. For example, scaling the design of a product or components can be done quicker with Digital Sketching than to redo them in Traditional Sketching.

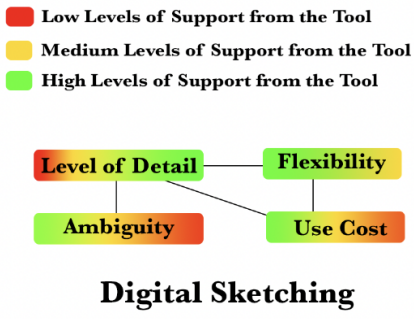


Fig. 7.15 Figurative Levels of Support From Digital Sketching for the Key DTCs (as an Association) in Internal Communication

Moreover, from a preliminary investigation on the relevant products and technologies, Digital Sketching could be more flexible for real-time co-editing than Traditional Sketching and CAD. As is seen in other tool-use conditions, Digital Sketching can maintain a certain freedom as a sketching tool. Besides, the digital platform enables Digital Sketching to separate teamwork into different editable layers or folders within one file and undo any mistakes flexibly. In comparison, the use of online co-editing CAD is seen in the industry, but the rigid nature of CAD in operation could make resolving co-editing complications time-consuming. When co-editing happens in *internal communication*, Digital Sketching may reduce the risk of triggering chains of complications and also avoid re-printing copies of traditional sketches to make any changes. The Flexibility and low-risk in time cost offered by Digital Sketching software products could encourage designers to be more constructive and disruptive in *internal communication* to trigger breakthrough ideas in the early phase.

The moderate levels of support for Ambiguity and Level of Detail offered by Digital Sketching could also contribute to a smoother transition from Traditional Sketching to CAD in the Early-Middle phases. For example, moderately ambiguous digital sketches can effectively convey a design to team members and still retain space for peer feedback and collaborations. Compared to Traditional Sketching, Digital Sketching is not so ambiguous that designers lose track of their original design concepts during in-team communications. It is also not as finished as CAD renderings that can deter other team members to make contributions, which is extremely important in this tool-use condition. It seems that Digital Sketching could be a "pathway" to ease transitions between its neighbouring tools in *internal communication* due to its broad and moderate levels of support for Flexibility, Use Cost, Ambiguity and Level of Detail.

7.3.2 The Barriers for Digital Sketching to Ease the Transitions

Apart from the above opportunities of Digital Sketching being a transitional "pathway" for its neighbouring tools, the study results also expose specific barriers for Digital Sketching to overcome to facilitate more efficient transitions of tools. As is shown in the experiment results (Chapters 5 and 6), the levels of support for the key Design Tool Characteristics (DTCs) are significantly different between the three design visualisation tools. When discussing the manifestations of Digital Sketching and its neighbouring tools in the Early-Middle phases in industrial design practice, certain DTCs of Digital Sketching stand out as potential barriers for using it in general as well as to ease the transitions.

In *externalisation*, the study shows that a few User-related Characteristics of Design Tools (UCs) and the associations between them are likely to be the barriers surrounding the use of Digital Sketching; namely, User Expertise, Expectation, User Loyalty, User Share and User Accessibility. Figure 7.16 summarises the potential barriers of using Digital Sketching in the Early-Middle phases as a transitional tool between its neighbouring tools in *externalisation*.

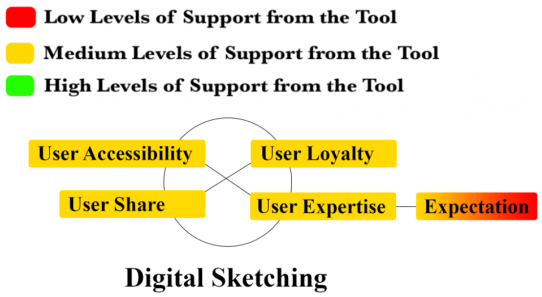


Fig. 7.16 Figurative Barriers of Digital Sketching in Externalisation

Some of these barriers could be stereotyped perceptions based on the designer's previous education or work experiences. For example, designers may have high expectations on the aesthetics when using Digital Sketching, even in the early design phases, which can significantly increase the Use Cost. This pattern of use could be caused by an outdated yet widespread impression of Digital Sketching as a beautifying tool for immersive polishing. Hence, the barriers identified in this study are not necessarily indestructible. Further tests on them may lead to breakthrough findings that can increase the utilisation of design tool resources.

According to the study results, the designer's User Expertise of Digital Sketching and their User Loyalty towards either Traditional Sketching or CAD could have negative impacts on the transitions. For example, when designers have a low level of User Ex-

pertise in Digital Sketching, they could be reluctant to use/learn it only for easier transitions without being aware of other benefits of using Digital Sketching in this tool-use condition.

Similarly, the current low User Loyalty towards Digital sketching among the investigated participants could be a reason that stopped the designers from using it in general, let alone using it for better tool transitions. In other words, the study indicates that designers could be aware of the advantages of Digital Sketching in *externalisation* but still choose not to use it if they have a low User Loyalty or User Expertise.

Another associated potential barrier in *externalisation* is the User Share and User Accessibility of Digital Sketching in the industrial design field. Even with the increasing User Share and User Accessibility in both education and industry, Digital Sketching devices are still less possessed among designers, design firms and design education institutions compared to Traditional Sketching and CAD.

In *external communication*, the barriers of using Digital Sketching are subtle, and it has been used as a transitional tool by many designers in practice. Figure 7.17 summarises the relevant DTCs and the associations between them. The potential barriers in this tool-use condition are Expectation, (which influences) Use Cost, User Share and User Accessibility. The related DTCs are also primarily User-related Characteristics of Design Tools (UCs).

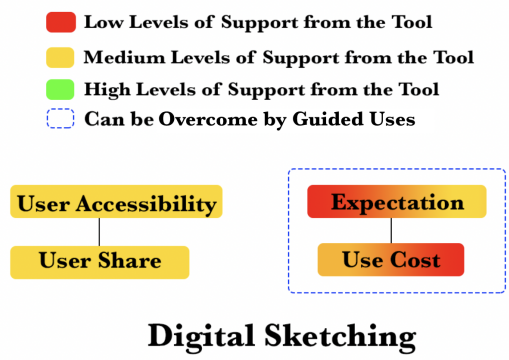


Fig. 7.17 Figurative Barriers of Digital Sketching in External Communication

As discussed in Section 7.2, Digital Sketching demonstrates its strengths in *external communication* during the Early-Middle phases in industrial design practice. However, the use and applications of Digital Sketching in this tool-use condition, including its use in easing the troublesome transitions, could be impacted by the relatively low User Share and User Accessibility. Based on the study results, User Share and User Accessibility of Digital Sketching at workplaces are significantly lower than with its

neighbouring tool. Continuous increases in Digital Sketching on User Share and User Accessibility in both industry and education could potentially reduce this barrier in the near future.

Sometimes, the high expectations on the resulting sketches generated by Digital Sketching could form another temporary barrier in *external communication* due to its influence on Use Cost. The current positive sentiments towards Use Cost of Digital Sketching in this tool-use condition are related to the fact that stakeholders' interests are dominating this tool-use condition. Hence, the time spent on a polished digital sketch is usually justified in designers' minds. However, if designers use Digital Sketching to generate photorealistic sketches for their clients in the Early-Middle phases, simply because it can be done with the tool, it would be unnecessary and time-consuming. Therefore, educating, guiding and an increasing awareness of what effective deliverables are in different design phases are also crucial for managing the Expectation on the visualisation tools, and hence a better selection and use of the tools.

In *internal communication*, the potential barriers that Digital Sketching is facing are Mobility, User Accessibility and User Share. As colour coded in Figure 7.18, the two UCs tend to be the more noticeable barriers than Mobility based on the study results.

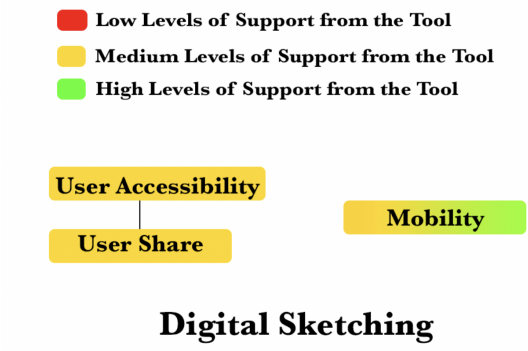


Fig. 7.18 Figurative Barriers of Digital Sketching in Internal Communication

Traditional Sketching and CAD show noticeable polarised levels of support on these three DTCs in *internal communication*. Traditional Sketching is considered extremely mobile and accessible and has the highest User Share among the three tools in the industry in this tool-use condition. For instance, designers can easily take their traditional sketches to communicate the design to other team members in their workplaces. Traditional Sketching enables the designers to work collaboratively and freely, including making changes to the sketches when having an in-team discussion. The study also indicates that CAD files are usually placed on the work computer, which is less mobile at workplaces unless there are cloud-based or local sharing services available.

However, long-distance collaboration enabled by online services could add new power to the Mobility of digital design tools in *internal communication*. According to the interview results, increasing numbers of designers have adopted Digital Sketching in this tool-use condition due to its growing Mobility. For example, more designers choose to use an iPad with sketching applications over a sketchbook during in-team meetings. To further improve the chances of Digital Sketching being a "pathway" to ease the transitions between Traditional Sketching and CAD, Mobility could be increased for more efficient uses. Enabling multiple freehand inputs on a scalable screen in Digital Sketching could be beneficial in this tool-use condition. With the development of mobile tablets and long-distance real-time collaboration software products, more creative uses of Digital Sketching in *internal communication* can be expected. Briefly, development in both hardware and software of Digital Sketching on Mobility is vital for its success to be a design visualisation tool with transitional capabilities.

There are some further aspects of Digital Sketching for tool developers to notice if enhancing the transitional capabilities of Digital Sketching is a goal; for instance, options for regulating Ambiguity, Level of Aesthetics and Level of Detail. Educators and designers need to be aware of the strengths and weaknesses of Digital sketching and create different ways to use it accordingly. Another example is the use of "block CAD" with Digital Sketching in a design team to work collaboratively on generating more Vertical Transformations.

The more we understand a design tool, the better we can develop and utilise it in design practice. Embracing Digital Sketching in both education and industry is important for exploiting available design resources to achieve more effective design outcomes on time. With the drop in prices and the expansion of platforms, Digital Sketching may be able to overcome the barriers to User Accessibility and User Share in the near future.

7.3.3 Summary: Strengths and Weaknesses of Digital Sketching Being a "Pathway"

In this study, Digital Sketching shows its strength in different tool-use conditions during the Early-Middle phases in industrial design practice. Whether it could be a "pathway" or not cannot be answered simply by yes or no. Because of the complexity of tool-use conditions in the industrial design process, and the purposes of design activities, the answer is given condition by condition.

The study provides a guideline that highlights and explains the promising opportunities to raise awareness of the strengths of Digital Sketching in different tool-use conditions,

and helps designers to decide when to use the tool. At the same time, the barriers faced with the tool are provided to raise awareness of its current weaknesses, so we can keep developing this tool accordingly.

In *externalisation* and *external communication*, where more data were collected from both the interviews and observations, Digital Sketching and its moderate nature on relevant Design Tool Characteristics (DTCs) show its strengths to be a "pathway" to ease troublesome transitions between its more bipolarised neighbouring tools. These strengths of Digital Sketching as a transitional tool primarily relate to the following DTCs and the associations between them: Accuracy, Ambiguity, Fidelity, Flexibility, Level of Aesthetics, Level of Commitment and Level of Detail. Based on the study results, identified barriers in these tool-use conditions are mostly User-related Characteristics of Design Tools (UCs) and the associations between them, including User Expertise, Expectation, User Loyalty, User Share and User Accessibility. Use Cost is noted mainly as a strength of Digital Sketching in externalisation and external communication, but can be affected by the weaknesses and becomes unfavourable if the tool is used unwisely.

In *internal communication*, where Digital Sketching is currently less seen used, discussion of its key DTCs also pictures some of its strengths to be further explored. Its potential advantages to be utilised in *internal communication* are related to these DTCs: Ambiguity, Flexibility, Level of Detail and Use Cost. Digital Sketching also faces barriers in this tool-use condition as well as in other tool-use conditions. Mobility, one of the Capability-related Characteristics of Design Tools (CCs), is noted to be a weakness of Digital Sketching in this tool-use condition. User Accessibility and User Share can also be weaknesses of Digital Sketching in assisting in-team communications.

According to the study results, most of the weaknesses of Digital Sketching being a transitional tool are UCs. Participants suggest that these UCs are related to their work and education experiences. Hence, the influences of *learning process* on the manifestation of tools in practice are discussed in the following section. Insights on this aspect of tool-use behaviours from the study results are given as follows.

7.4 The Use of Digital Sketching and the Learning Process

Apart from the three tool-use conditions discussed above, the study also shows some unexpected findings on how key DTCs in the *learning process* during a designer's formal education could influence the selection and use of tools in practice. To have a more comprehensive understanding of Digital Sketching, the *learning process* of this tool in

formal education and its further influences are discussed in this section.

In Subsection 5.9.4, interview results indicate that many practising designers are not very positive about the *learning process* of Digital Sketching in their formal education. The sentiment results about their *learning process* – in a retrospective view – of Traditional Sketching and CAD are relatively more positive. This phenomenon could occur partly due to the lower User Share and User Accessibility of Digital Sketching in formal design education back when the majority of the participants undertook their university studies (approximately 5–10 years ago). User Share in this study also indicates how many units, courses or hours of learning Digital Sketching were scheduled in their design degrees. As suggested by the interview participants, Digital Sketching has a relatively lower User Share compared to its neighbouring tools in education and industry. Some participants also view Traditional Sketching and CAD as the more fundamental tools in the industrial design field, which may also be influenced by their former educators and educational institutions.

However, the emergence of Digital Sketching in the field and applications of it in industry practice now urge education systems to embrace this design visualisation tool more. Otherwise, as is shown in the interview results, the designers without a substantial *learning process* of Digital Sketching in formal education may experience more emotional and psychological struggles when they need to learn and use it in practice. The study suggests that an unsatisfying or insufficient *learning process* of Digital Sketching in formal education could have long-term negative impacts on its future *learning process*, as well as the resulting User Expertise and User Loyalty towards the tool.

Similarly, as discussed in Subsection 7.2.4, the earlier that formal education can introduce a design tool, the higher chance that students may form a better-guided understanding of the use of the tool. Students show a tendency towards the continuous use of a design visualisation tool in the ways that they have learned in their formal education. For instance, the relatively universal introduction of Digital Sketching as a tool to polish up traditional sketches (10–15 years ago) in design education contributes to the success of using Digital Sketching in *external Communication* – even now in practice. From some textbooks on sketching in product and industrial design back then – e.g., from Eissen and Steur (2007) – most Digital Sketching examples shown are traditional sketches polished by Digital Sketching. In other words, formal education is vital for designers to form appropriate expectations of a design tool and make sensible selection and use of it. Whether the Expectation of the tool is satisfied/matched in practice or not also seems to significantly influence their choices to continue to use the tool or not in practice. Since Digital Sketching was not necessarily introduced in formal design education thoroughly back then, and indeed not introduced as a tool for early *exter-*

nalisation, the limited current use of Digital Sketching in these tool-use conditions is traceable.

Arguably, if other effective and diverse patterns of the use of Digital Sketching in the Early-Middle design phases from (or indicated by) the study results can be introduced to education as soon as possible, students may be on a better track to build User Expertise and generate User Loyalty of the tool, and have suitable levels of Expectation when using it in practice.

7.5 Chapter Summary

In this chapter, the answers to the three research questions of this study are discussed based on experiment results. Regarding research question 1, how to compare Digital Sketching with other design visualisation tools in industrial design, the use of the Design Tool Characteristics (DTCs) framework is further evaluated. The DTCs framework is first created and proposed after the *review-based descriptive study I*. In the experiments, the DTCs framework was used as a basis to analyse and compare Digital Sketching with its neighbouring tools. The perceptions of the design tools and related tool-use behaviours of designers from the experiments are coded with this framework, and the resulting comparable data effectively supports the findings in this study.

To be specific, the DTCs framework provides a considerably comprehensive number of universal design tool characteristics from the perspectives of both design tools and design tool users, which first ensures the breadth of the comparisons. Furthermore, the framework also contributes to the depth of the analyses by enabling a multifaceted understanding of the tools' natures that extends beyond its individual characteristics to the associations between them. Briefly, this framework offers an approach to understand, compare and evaluate Digital Sketching as well as other traditional, emerging and hybrid design visualisation tools in 3D design fields. It is essential to have this method, as it enables us to have an in-depth understanding of the strengths and weaknesses of the design visualisation tools versus each other, which can advantage us in both education and industry planning and practice.

For research question 2, the manifestation of Digital Sketching in industrial design practice during the Early-Middle design phases is discussed in different tool-use conditions. Interview and observation studies with practising industrial designers are used to understand the patterns of use and applications of Digital Sketching in practice. The DTCs framework is used to explain the reasons behind its current limited uses and also reflect on the comparative uses with its neighbouring tools for a more comprehensive

understanding. The discussion is conducted from two perspectives; namely, the time efficiency and the resulting effectiveness of using Digital Sketching in each tool-use condition.

In the Early-Middle phases, the current use of Digital Sketching is limited to *externalisation* and *internal communication*, which is explained by the relevant key DTCs. Some User-related Characteristics of Design Tools (UCs) of Digital Sketching have shown negative impacts on its use, especially the time efficiency of the use of this tool. One of the most influencing factors is the stereotyped understanding of the tool's capability. For example, many designers believe that Digital Sketching requires a clear mental image to work with that, in turn, limits them to adopt it during ideation and in-team communication. However, there are positive supports offered by Digital Sketching in terms of the resulting effectiveness. For example, the study shows that the positively associated key DTCs in externalisation could facilitate the development of design variations in the middle phase.

The limited employment of Digital Sketching also leads to less collected data regarding its use in *internal communication*. According to the experiment results, it seems that Digital Sketching, at the moment, is not ideal for in-team communications. A potential we see from Digital Sketching in supporting in-team communications could be its Flexibility for real-time international online collaborations, especially in the context of the rapid globalisation and virtualisation of contemporary design workplaces.

The current primary use of Digital Sketching in practice is for *external communication*, and its key DTCs and their associations in this tool-use condition further explain this pattern of its use. The resulting digital sketches could work effectively to "hook in" stakeholders in the Early-Middle phases, when designers are happy to spend a little bit more time in this tool-use condition. Study results also suggest that Digital Sketching is not just about beautifying design representations; for it could not only convey the design concepts to the stakeholders but also reserve space for client feedback and further design development.

To answer the research question 3, the literature review first highlights some troublesome transitions between Traditional Sketching and CAD according to their bipolarised natures when compared to each other. The theoretical potential of Digital Sketching being a "pathway" to ease these transitions is proposed after the *review-based descriptive study I*. Discussion in this chapter further explains the troublesome transitions between Traditional Sketching and CAD in detail with specific relevant DTCs, then argues the possibility for Digital Sketching to ease them based on its manifestation in practice.

The answer as to whether Digital Sketching is a pathway varies in different tool-use conditions due to the different expectations and design activities involved. In *externalisation*, Digital Sketching shows great support on offering moderate levels of relevant key DTCs compared to the polarised characteristics of Traditional Sketching and CAD. Moreover, these DTCs, together with the associations between them, can generate positive support for Digital Sketching being a transitional tool. Unfortunately, the use of Digital Sketching as a "pathway" is little seen in practice, which is also explained by the barriers identified; e.g., high expectations on the resulting sketches cause unnecessary time cost.

Digital Sketching also shows excellent support in *external communication* as a transitional tool. This study shows that some barriers related to the UCs could potentially be overcome by having a clear design intent, and the principle could be applied to other tool-use conditions. For example, stakeholder considerations are used to justify the high Use Cost in this tool-use condition. Hence, it is possible to overcome some barriers formed from relevant UCs in other tool-use conditions by re-framing and rationalising designers' expectations and intents of design visualisations. In *internal communication*, the weaknesses of Digital Sketching tend to be seen in Mobility, User Accessibility and User Share.

In summary, Digital Sketching could be a "pathway" to ease troublesome transitions in *externalisation* and *external communication*. To adopt the further use and applications of Digital Sketching in general, and as a transitional tool during the Early-Middle phases in industrial design, weaknesses related to certain UCs need to be overcome. Examples of overcoming UCs-related barriers in *external communication* indicate that they could be regulated by having explicit design intents, having a better understanding of the tools, and embracing new technologies in education and industry. For education, a discussion around the influences of the learning processes of design tools and the importance of embracing new technologies is also given in Section 7.4.

In this chapter, discussions based on the literature review, interview and observation results are given to form answers to the three research questions. Aiming at picturing a more comprehensive and up-to-date understanding of Digital Sketching and the use of it in industrial design practice, the manifestation of this tool is discussed, explained and compared with its neighbouring tools. By exposing its comparative strengths and weaknesses, we have further explored the possibility of it being a transitional tool to ease the troublesome transitions between its neighbouring tools. All in all, we have a more comprehensive and solid foundation to further exploit this powerful, emerging design visualisation tool to achieve more effective design representations on time.

CHAPTER 8

CONCLUSIONS

The powerful affordances of Digital Sketching in theory are not fully utilised in its limited and relatively conservative uses in industrial design practice, which formed the research problem of this study. The research investigated the use of Digital Sketching and its neighbouring tools with practising designers to understand causes and explore solutions to this problem. Three research questions were posed. This chapter first describes how the research aim and objectives were addressed. Then, based on the study results, conclusions are drawn as answers to the research questions. As such, a more comprehensive and up-to-date understanding of Digital Sketching is given for further exploiting its use to achieve effective design outcomes on time. The practical implications of the study results and the study's contribution to knowledge are discussed. Finally, future work and research projects are recommended.

8.1 Addressing the Research Aim and Answering the Research Questions

According to the literature review and the author's empirical design observations at workplaces in various countries, Digital Sketching currently has limited use in practice and relatively limited knowledge in the domain literature compared to more traditional design visualisation tools; e.g., Traditional Sketching and CAD. However, literature also shows the theoretical affordances of Digital Sketching are promising for more diverse use and for applications in industrial design practice. The study aims at providing a more comprehensive and up-to-date understanding of Digital Sketching and to further guide its use in industrial design practice and free up the design resources. Three research questions and their objectives were proposed with relevant research activities conducted. In this section, conclusions of the research questions are described. Figurative illustrations are used as an intuitive way to show and summarise the findings of the study.

8.1.1 An Approach to Analyse Design Visualisation Tools in Industrial Design

To be able to analyse and understand Digital Sketching in practice, the study discovered that an effective approach to evaluate and compare it with other design visualisation tools was needed. Hence, the first research question is proposed as follows:

Research Question 1*: How to compare Digital Sketching with other design visualisation tools?*

A comprehensive Design Tool Characteristics (DTCs) framework is created and used in this study for this purpose. Based on the literature review and the experience of using the DTCs framework to analyse Digital Sketching and its neighbouring tools in this study, the answer to this research question is presented as:

The DTCs framework can be a helpful and effective approach to understand, analyse and compare Digital Sketching with other design visualisation tools in detail, which could also be used in relevant tool studies in the industrial design field.

In this subsection, how objectives of this research questions were met are summarised first, followed by the strengths and limitations of the DTCs framework identified from this study.

- **Objective 1:** Identify the most common neighbouring tools of Digital Sketching

  According to the literature review results, Traditional Sketching and CAD Modelling were identified as the most common neighbouring tools of Digital Sketching in industrial design practice.

- **Objective 2:** Understand the target and potential design phases for Digital Sketching to achieve its potentials

  Based on the theoretical affordances of Digital Sketching identified in the literature and the expectations of different phases during the industrial design process, the Early-Middle phases are the targeted phases for Digital Sketching to be further utilised.

- **Objective 3:** Build a detailed framework for conducting comparisons of design visualisation tools

  Literature shows the use of universal design tool characteristics frameworks can be a way to compare different design tools. However, the literature review also suggests that a more extensive framework is needed to be able to compare Digital Sketching to existing tools in depth. Therefore, a more comprehensive Design

Tool Characteristics (DTCs) framework was built based on a literature review of design visualisation tools in 3D design fields to conduct comparisons between Digital Sketching and its neighbouring tools in the targeted design phases.

In this study, the Design Tool Characteristics (DTCs) framework is used to guide the investigation of the use of Digital Sketching in practice and conduct comparisons between Digital Sketching and its neighbouring tools; namely, Traditional Sketching and CAD. The strengths and limitations of the DTCs framework discovered in analysing and comparing design visualisation tools are figuratively illustrated in Figure 8.1.

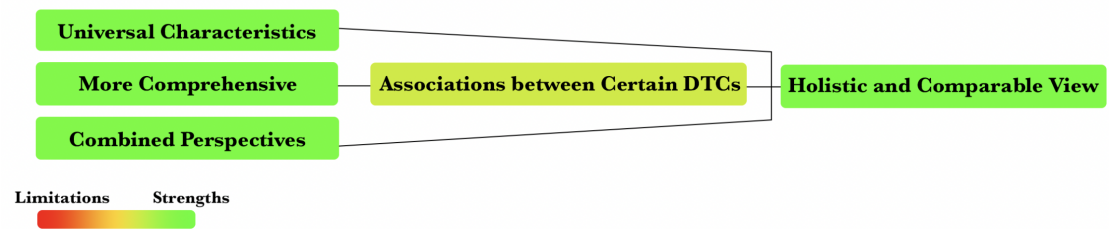


Fig. 8.1 Strengths and Limitations of the DTCs Framework in Understanding and Comparing Design Visualisation Tools

According to the results that are presented and discussed in Chapters 5, 6 and 7, the DTCs framework was effective for comparing Digital Sketching with its neighbouring tools in the industrial design field. In particular, the universal characteristics of the framework helped to conduct the comparisons in a way that would have been otherwise challenging. For example, according to the experiment results, the perceptions of how clear a mental image of the design should be to start using Traditional Sketching, Digital Sketching or CAD are very different, yet this consideration is vital for designers to choose which tool to use during the design process. By generalising and defining this factor as the Fidelity in the DTCs framework, it becomes a comparable characteristic shared by the design visualisation tools.

Furthermore, the comprehensiveness of the framework, combined with the rich data gathered in the experiment, enabled an in-depth understanding of how the different characteristics are associated in the designer's view and subsequent decision making around the selection and use of tools. The comprehensiveness of the DTCs framework creates a multifaceted understanding of the tools (as discussed in Chapter 7).

However, the results also suggest that certain DTCs in the framework are associated, which can make their distinctions a challenging task. In other words, with increased comprehensiveness come more nuanced definitions which, in turn, makes coding more challenging. The issue is unavoidable to a certain extent. Similar to the way that extra

data or sampling leads to more noise, a more comprehensive DTCs framework leads to more nuanced and potentially more challenging coding. The study also shows that the associations between the DTCs can vary depending on the tool-use conditions, which may make the coding more complex. As shown in Figure 8.1, the associations between the DTCs are identified as a strength with limitations. The reason is that even though the associations increase the difficulty of coding and analysis, they also enable a multi-faceted understanding of the tools.

The success of applying the framework is thus contingent on the users' familiarity with the framework. For instance, according to the independent coder during the interview inter-rater reliability test, it took time for the coder to become familiar with the framework. The comparison results in this project are effective, but the efficiency of using the framework can be influenced by the user's familiarity and understanding of the DTCs in the framework. As an illustration, the independent coder modified a few coding results after gaining a more in-depth understanding of the definitions of specific DTCs.

All in all, this thesis illustrates that the DTCs framework can be a helpful and effective approach to compare Digital Sketching with other design visualisation tools in industrial design, which can also be used to analyse and compare other traditional, emerging or hybrid design visualisation tools in 3D design fields. Future work can be done to further improve the methods of using this framework. This conclusion is drawn based on the study results and discussions in Chapter 7.

8.1.2 Why and When to Use Digital Sketching

Research question 2 is posed to provide evidence to form a more comprehensive and up-to-date understanding of the manifestation of Digital Sketching in practice, and hence reveal and guide its more efficient and effective use.

Research Question 2: *How does Digital Sketching manifest in industrial design practice during the Early-Middle design phases?*

Interviews and observations with practising designers are used to understand what they think of Digital Sketching and how they use it in practice. These patterns of use and application of Digital Sketching among practising designers are defined as the manifestation of this tool in practice. The Design Tool Characteristics (DTCs) framework was used to guide the analysis of the manifestation of Digital Sketching. The levels of support offered by Digital Sketching to provide a time-efficient design process and reach effective design outcomes were revealed, explained and evaluated. This research

question was answered with respect to levels of support for the key and essential DTCs in the Early-Middle phases of the industrial design process. Note that the key DTCs are those most frequently mentioned in the interviews, and that the essential DTCs are key DTCs shown in more than one tool-use condition.

The manifestation of Digital Sketching in practice concurs with the discovery in literature that it is primarily used to generate polished design representations for communicating with clients and other non-designer stakeholders. The study shows that Digital Sketching, when used with reasonable expectations, can also be used effectively to generate, externalise and modify design concepts for designers themselves. Digital Sketching has limited use for in-team communication and is not considered an ideal tool for it at the moment, but its potential for this purpose is clear, based on the development of relevant technologies. Therefore, Digital Sketching could have more diverse patterns of use and applications during the Early-Middle phases in the industrial design process according to the support it can offer based on its characteristics.

From the study results and discussions, the primary beneficial characteristics of Digital Sketching are Ambiguity, Flexibility, Level of Aesthetics, Level of Detail and Vertical Transformation. The main concerns surround the user-related characteristics User Loyalty, Expertise and User Accessibility. These are shown to have certain connections to the learning process of the tool in formal education.

However, the DTCs and their associations that are either beneficial or regarded as limitations are specific to the tool-use conditions. The conclusions on the manifestation of Digital Sketching in each tool-use condition are given after the summary on the objectives of research question 2.

- **Objective 1:** Investigate the current use of Digital Sketching in industrial design practice

  The use of Digital Sketching and its neighbouring tools in the industrial design process were investigated by interviews and observations with practising designers from three different design firms. A working category of four different design tool-use conditions in industrial design practice was built to break down the complexities of tool-use behaviours and perceptions for discussion.

- **Objective 2:** Explain the reasons behind the limited use of Digital Sketching in practice

  With the DTCs framework, the reasons behind the limited and conservative patterns of use and applications of Digital Sketching in practice were explained

against specific key DTCs (DTCs most frequently mentioned in the interviews) and associations of these DTCs under each tool-use condition.

- **Objective 3:** Reflect on the strengths and limitations of Digital Sketching in comparison with its neighbouring tools

  To achieve this research objective, the interview and observation investigations were conducted with Digital Sketching and its neighbouring tools. The strengths and limitations of Digital Sketching are revealed in comparison with Traditional Sketching and CAD.

To be specific, Digital Sketching shows strengths in offering broader levels of support for key DTCs and more balanced associations between these DTCs during the Early-Middle phases in industrial design. In *externalisation*, as illustrated in Figure 8.2, the manifestation of Digital Sketching in practice is reflected on a few associations of specific DTCs.

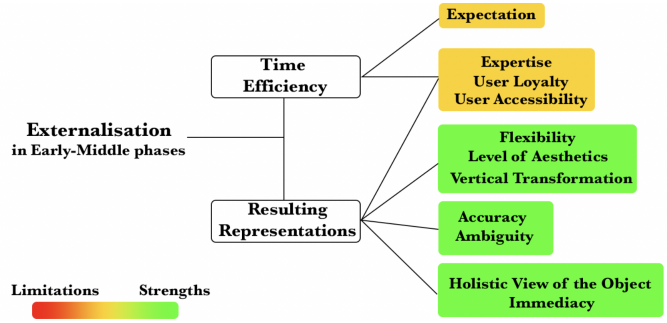


Fig. 8.2 Manifestation of Digital Sketching in Externalisation in Industrial Design

Digital Sketching offers a moderate level of Flexibility and Ambiguity for designers to keep generating and developing design concepts with a moderate Level of Aesthetics, Level of Detail and Accuracy that won't necessarily be too time-consuming. To ensure the efficiency of this tool, the Expectation of the design representation from the designers should align with the expected deliverables of the design process. For example, not over-polishing the digital sketches in the early design phase. When using Digital Sketching in *externalisation*, other premises to ensure effective design results on time are as follows: 1) designers are able to access this tool and have an adequate level of Expertise with it; 2) designers are able to adjust their pre-existing User Loyalty of its neighbouring tools if applicable.

In industrial design practice, Digital Sketching has been used primarily for beautifying traditional sketches that are usually made for clients and other non-designer stakeholders. Digital Sketching is more powerful when it is used to generate, visualise and

present design concepts in this tool-use condition, defined as *external communication* in this study. As illustrated in Figure 8.3, these key DTCs and their associations reveal its patterns of use and applications, and why.

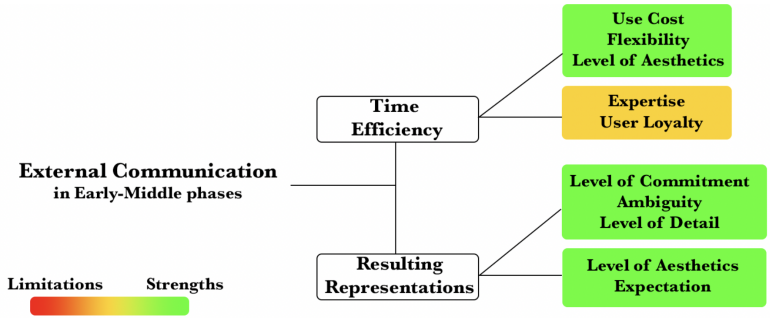


Fig. 8.3 Manifestation of Digital Sketching in External Communication in Industrial Design

In *external communication*, Digital Sketching is flexible and fast for generating visually appealing design representations that match the expectations of both parties; namely, the designers and the stakeholders. Its moderate levels of Ambiguity also perfectly suit the needs of both parties in the Early-Middle phases, which is associated with a moderate Level of Detail and Level of Commitment. The associations between these DTCs explain its use to effectively convey the design concepts to the stakeholders and stimulate constructive feedback from them. They also allow designers to further develop the concepts in later design phases. Similarly, for more designers to successfully adopt this tool in *external communication* and use it efficiently, it is important that they have an adequate level of Expertise and adjust their pre-existing User Loyalty to its neighbouring tools (if applicable).

For designers to regulate their Expectation and User loyalty towards Digital Sketching in this tool-use condition, as well as attain an adequate level of Expertise, the *learning process* likely plays a critical role. As seen from the study results, the current limited and conservative patterns of use and applications of Digital Sketching are related to a previous limited formal education regarding this tool; to be specific, back when most of the participating designers in this study did their formal design education (5–10 years ago). An increase of User Share and User Accessibility of Digital Sketching could help future designers to further adopt this powerful tool in their practice. Importantly, this finding could be expanded to other emerging design visualisation tools. A timely, satisfying and thorough *learning process* of emerging design tools in our formal design education could empower future designers with wise usages and flexible adaptions of leading-edge tools later in their careers.

For internal communication, as is illustrated in Figure 8.4, Digital Sketching is not yet

an ideal tool. This is mostly due to the technological restrictions on its Mobility and User Accessibility. For example, interactive multi-input tablets are not widely developed nor available at many workplaces. Hence, Traditional Sketching is considered the primary tool in this tool-use condition.

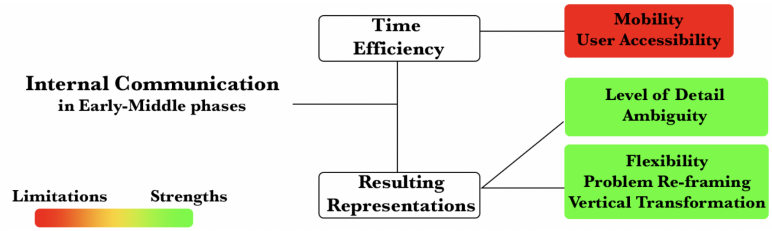


Fig. 8.4 Manifestation of Digital Sketching in Internal Communication in Industrial Design

Based on study results and discussions, Digital Sketching also shows advantages on specific DTCs that may help to achieve effective design results in this tool-use condition. These DTCs and the associations between them that can be offered by Digital Sketching are summarised in this study to help designers understand more of its strengths. To be specific, Digital Sketching does not require high Fidelity for the mental images, so designers can feel more flexible to work with it. Digital Sketching is also flexible for making design modifications and iterations during in-team communications. As well, Digital Sketching offers more balanced associations between Level of Detail and Ambiguity, which can be utilised for in-team communications during the middle phases.

From reviewing the development of relevant technologies, the digital platform seems to empower Digital Sketching with strengths that can be used to assist *internal communication* – both now and soon. For example, online real-time collaborations can be conducted internationally with Digital Sketching, which will become a more and more common situation in our increasingly globalised and virtualised contemporary workplaces. Similarly, the constantly growing Use Share in the industry and the more digital mindsets of new generations of designers could contribute to the changes of the manifestation of Digital Sketching in this tool-use condition in the near future.

All in all, the study suggests that Digital Sketching could gain more diverse patterns of use and applications during the Early-Middle phases in the industrial design process according to the support it can offer based on its characteristics.

8.1.3 A Pathway to Ease Transitions Between Traditional Sketching and CAD

The literature suggests there are troublesome transitions between Traditional Sketching and CAD modelling based on their bipolarised affordances/natures, and Digital Sketching shows theoretical potential to ease the transitions (Chapters 1 and 2). Research question 3 and its relevant research objectives were proposed to explore this possibility further.

Research Question 3: *Could Digital Sketching be a "pathway" to ease transitions between Traditional Sketching and CAD during the Early-Middle design phases in industrial design?*

The manifestation of Digital Sketching in practice forms a basis to discuss the answer for this research question. The study results help to expose and explain some of the essential yet troublesome transitions between Traditional Sketching and CAD, which also help to explore the possibility of Digital Sketching being a solution. Based on the discussions supported by the study results, the answer to research question 3 is presented as follows.

In externalisation and external communication, Digital Sketching can be used as a "pathway" to ease some troublesome transitions between Traditional Sketching and CAD during the Early-Middle phases in industrial design practice. However, Digital Sketching is not yet considered a transitional tool between its neighbouring tools in internal communication.

The study results reveal both opportunities and barriers surrounding Digital Sketching as a transitional tool between Traditional Sketching and CAD. The opportunities primarily lie in a few essential Design Tool Characteristics (DTCs) and their associations. These essential DTCs of Digital Sketching, identified in this study, are Accuracy, Ambiguity, Fidelity, Level of Aesthetics, Level of Detail and Use Cost. They were first noted from the interview results then examined by the observations. They display strong influences on the manifestation of Digital Sketching in practice and show bipolarised differences in its neighbouring tools. The weaknesses of Digital Sketching being a "pathway" have been discovered to be dominantly user-related characteristics. The conclusions are provided (based on tool-use conditions) after the description of how the objectives of this research question were met.

- **Objective 1:** Explain the troublesome transitions between Traditional Sketching and CAD

  Troublesome transitions between Traditional Sketching and CAD Modelling were

firstly identified from the literature review based on their bipolar affordances. The troublesome transitions are further defined and explained by the bipolarised DTCs of Traditional Sketching and CAD shown in the interview and observation results.

- **Objective 2:** Explore the opportunity to solve some of the issues experienced with Traditional Sketching and CAD Using Digital Sketching

  The theoretical potential of Digital Sketching on easing the transitions was proposed after the literature review (Chapters 1 and 2). The strengths of Digital Sketching on easing the particular transitions between its neighbouring tools are discussed based on the manifestation of the three tools in practice.

- **Objective 3:** Explain the limitations of using Digital Sketching in Early-Middle Design Phases in industrial design practice

  Similarly, for Digital Sketching to be a "pathway" to ease the transitions between its neighbouring tools, there are limitations. The weaknesses of Digital Sketching as a transitional tool are discussed under each tool-use condition due to the diversity of design deliverables and expectations.

In *externalisation* and *external communication*, as illustrated in Figures 8.5 and 8.6, Digital Sketching offers good support on various key DTCs that are relatively bipolar in its neighbouring tools. Arguably, they are the opportunities where the strengths of Digital Sketching can bridge the gaps between its neighbouring tools. Also, weaknesses of Digital Sketching being a transitional tool are shown in the figures as barriers to overcome.

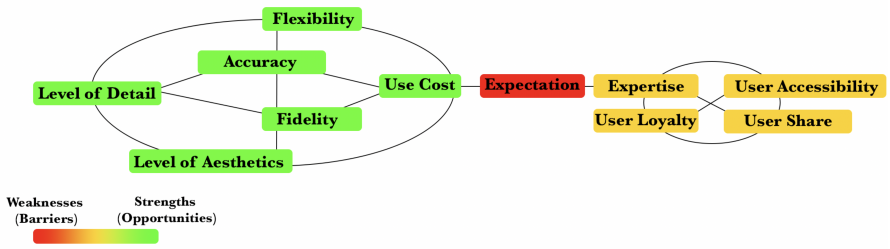


Fig. 8.5 Digital Sketching to Ease Transitions in Externalisation

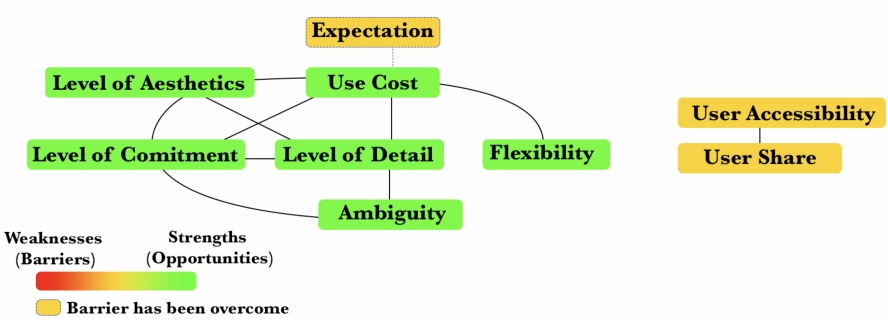


Fig. 8.6 Digital Sketching to Ease Transitions in External Communication

In these two conditions, the strengths of Digital Sketching being a "pathway" are shown by its moderate and broad levels of support for Ambiguity, Accuracy, Flexibility, Fidelity, Level of Detail, Level of Aesthetics, Level of Commitment and Use Cost. Compared to the more polarised support offered by its neighbouring tools on these DTCs, Digital Sketching can work as a transitional tool to ease the sharp transitions.

Barriers can be seen that are based on the weaknesses of Digital Sketching on particular User-related Characteristics of Design Tools (UCs). User Accessibility and User Share are noted as receiving insufficient support from Digital Sketching. The Expectation of the quality of digital sketches is generally high, which may pressure designers to invest their time in overly polishing their sketches. When Digital Sketching is used in *external communication*, the Use Cost can be justified by the designers based on the stakeholders' interests. However, this use of time is not seen as necessary in *externalisation*. The high Expectation of Digital Sketching could be a stereotypical impression rather than an actual requirement, especially when the focus on visualisation in *externalisation* is principally about generating more design concepts. Besides, the Expertise of the designers on Digital Sketching is a barrier to overcome for using it to ease the troublesome transitions.

It is worth noting that most of the barriers of Digital Sketching on UCs could be overcome by having explicit design intents; having an up-to-date understanding of the tools; and embracing new technologies in tool development and design education.

In *internal communication*, Traditional Sketching is a dominant tool due to its high Mobility, Flexibility, User Accessibility and low Use Cost during the Early-Middle phases. As highlighted in Figure 8.7, Digital Sketching currently shows weaknesses in supporting Mobility, User Share and User Accessibility. These weaknesses influence its Use Cost in this tool-use condition and ultimately affect the possibility to be a transitional tool between its neighbouring tools.

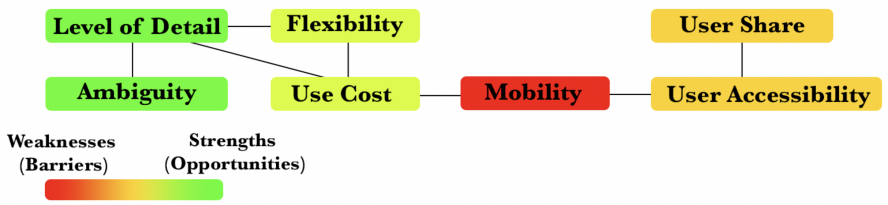


Fig. 8.7 Digital Sketching to Ease Transitions in Internal Communication

However, supporting technologies and more affordable digital tablets are becoming more and more available, which can help Digital Sketching to overcome the related barriers. At the same time, levels of support on certain DTCs offered by Digital Sketching show its potential to be a transitional tool. For example, Digital Sketching can retain moderate levels of Ambiguity for effective design iterations during in-team communications. Digital Sketching is also flexible in supporting both Aesthetic and Engineering Detail development, which is critical in the middle design phase. Online, real-time collaborations in Digital Sketching, enabled by its digital platform, would also assume a more important role in the growing globalised and virtualised contemporary workplaces in the industrial design field.

To conclude, Digital Sketching can be a "pathway" to ease specific troublesome transitions between Traditional Sketching and CAD in *externalisation* and *external communication* during the Early-Middle phases in industrial design practice. Against Digital Sketching being more widely adopted as a "pathway" in these tool-use conditions, user-related issues have formed major barriers surrounding it. However, the study shows that many of these user-related issues could be further resolved; e.g., offering thorough and timely training in formal education or having clear design intents and appropriate expectations at each design phase in practice. Digital Sketching also shows potential in *internal communication*. However, it is not yet an ideal transitional tool to ease transitions in this tool-use condition, mainly due to technological and user-related issues. The next steps to empower our designers with this tool are embracing relevant emerging technologies in both education and industry, and continuously developing and optimising Digital Sketching software and hardware products and making them more accessible.

8.2 Conclusions of the Thesis

The overall conclusions from the thesis are summarised and presented in this section. The study suggests that Digital Sketching could have more diverse patterns of use and applications in the Early-Middle phases of the industrial design process. Digital Sketching can support conducting time-efficient design processes/activities and achieving ef-

fective design outcomes according to its manifestation in industrial design practice. Apart from within-team communications, Digital Sketching shows its capability of not only being a useful tool to assist designers but also a transitional tool to be used between Traditional Sketching and CAD.

The study concludes that the main "enabling" Capability-related Characteristics of Design Tools (CCs) of Digital Sketching centre on Ambiguity, Flexibility, Level of Aesthetics, and Level of Detail, and the balanced associations between these characteristics. In general, Digital Sketching offers flexible operations to generate, visualise and modify both technical and aesthetic details of the design concepts. For external non-designer stakeholders, Digital Sketching provides a balanced approach to have certainty in the design concept while allowing feedback, modifications and further development of the design. The Level of Aesthetics offered by Digital Sketching is another notably important characteristic to catch the attention of the stakeholders and show off the designers' profession. The study suggests the same balance can be struck when designers use Digital Sketching to visualise design concepts for themselves in the earlier phases. However, doing so requires relevant User-related Characteristics of Design Tools (UCs) to be overcome; e.g., overly high expectations of the results or inadequate levels of expertise with the tool.

In other words, current conservative and limited patterns of use and applications of Digital Sketching in industrial design practice are motivated by designers' (the tool users') concerns and the resulting behaviours that arise from their expectations and lack of training. Data showed that Digital Sketching training in formal education has long-term impacts on designers' acceptance and usage of this tool in practice. The study hence concludes that the learning experience of Digital sketching in formal education likely has a long-term impact on designers' tool-use mindsets and behaviours.

While technology is rapidly advancing, the technical Mobility of Digital Sketching falls short from the perspective of internal communication. Traditional Sketching offers excellent Mobility and User Accessibility. With respect to CAD, its master modelling and online, real-time file-sharing/editing capabilities also offer advanced Mobility. To be a useful tool in *internal communication*, Digital Sketching has its potential and strengths, but improvement in Mobility and User Accessibility is vital.

In terms of being a transitional tool between Traditional Sketching and CAD, Digital Sketching has characteristics that make it suitable to be a "pathway" and to be a useful tool in specific scenarios. However, doing so will require design practitioners to overcome the expectation and expertise issues raised above, and encourage education and industry to embrace this tool and the relevant emerging technologies.

Last, but not least, during this study of Digital Sketching, the Design Tool Characteristics (DTCs) framework is comprehensive and effective to use. However, with greater density of the characteristics comes more nuance and potential for noise during the analysis. Future work on improving methods of use to optimise the influence of this factor and improve its utility can be expected.

8.3 Practical Implications of the Study

As illustrated in Figure 8.8, the study can encourage and guide more diverse, effective and purposeful patterns of use and applications of Digital Sketching in industrial design practice, and hence free up design resources. It would also encourage and guide more research projects into understanding emerging design visualisation tools, and offer more effective approaches to deliver and use them in education and industry, thus prompting design tool development in the industrial design field.

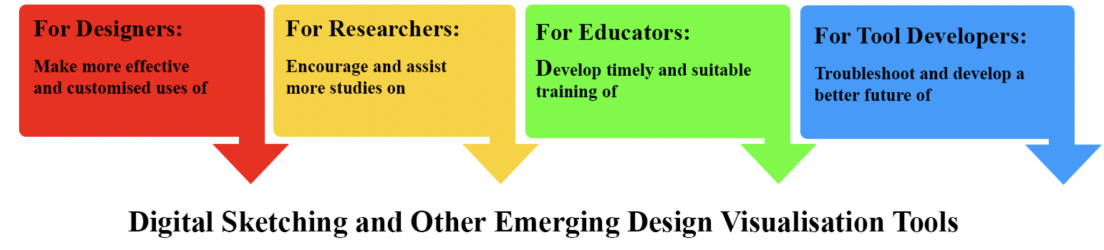


Fig. 8.8 Practical Implications of the Study

To be specific, the study provides a more comprehensive understanding of Digital Sketching from a combined perspective of design practitioners and design practice, which is lacking in the literature.

For researchers, a more comprehensive understanding of Digital Sketching opens up further discussions on its manifestation and diverse applications in industrial design and in other 3D design fields. Additionally, the Design Tool Characteristics (DTCs) framework now facilitates more studies on understanding and evaluating other leading-edge, emerging or hybrid design tools and techniques in the industrial design field. Thus, the in-depth knowledge of Digital Sketching provided in this thesis not only deepens the domain knowledge but also forms a base to further explore and utilise this tool and other emerging tools in the field. The study also offers an industrial design process model with phase-based deliverables as well as a category of tool-use conditions, which could help researchers to contextualise relevant design tool studies in our field.

For practising designers, the strengths and limitations of Digital Sketching in differ-

ent tool-use conditions during the design process are now explained more precisely and clearly. A more up-to-date and comprehensive understanding of Digital Sketching could lead to more effective and customised patterns of use and applications in industrial design practice. It helps to raise awareness of the strengths of this tool among design practitioners and reduce stereotypical impressions of it for effective utilisation in our community. Especially with new developments in relevant technologies, Digital Sketching is continuously improving in various ways to assist designers further. For example, more affordable and accessible Digital Sketching tablets can now offer more intuitive eye-hand coordination with built-in display/touch screens. Emerging Digital Sketching platforms based on XR (Cross Reality; e.g., Virtual Reality and Augmented Reality) technologies could be another promising direction for this tool to advance designers in the future.

Exploring the possibility of Digital Sketching being a transitional tool further exposes existing troublesome transitions between Traditional Sketching and CAD in the Early-Middle phases in industrial design practice. These transitions could affect the time-efficiency of the design processes/activities and the effectiveness of the resulting design representations. The study suggests where Digital Sketching could be a "pathway" to ease specific transitions in the Early-Middle phases, and why. This finding, in turn, could also be used as a basis for designers to use Digital Sketching with clearer design intents.

For design educators, research on design visualisation tools, including this study, can inform choices on when and how to deliver a new or emerging design tool to students. The study also reveals the importance of embracing new design tools and techniques in formal education, and hence ensure the adaptability of future designers to new technologies in design practice. Training well-selected, emerging design tools could help to prepare future design practitioners for their workplaces, not only in terms of their skill-sets but also their mindsets and ability to choose from thousands of new, emerging or hybrid design tools in the future.

By revealing the strengths and limitations of Digital Sketching, the study could also prompt future design tool development. For the design tool developers, the expectations from designers on Digital Sketching are clarified, and many limitations of this tool are highlighted to be resolved. This study offers a way for design tool developers of Digital Sketching to connect and understand their targeted tool users – the practising designers. At the same time, the Design Tool Characteristics (DTCs) framework could be of benefit to design-tool developers to conduct research and make decisions on how tools should support designers. Other practical implications of the DTCs framework were given in Chapter 7.

8.4 Contribution to Knowledge

The study aimed to provide a more comprehensive and in-depth understanding of Digital Sketching. Digital Sketching is an emerging design tool that currently shows potential in theory but has limited use in industrial design practice. In literature, there are fewer studies on Digital Sketching compared to its neighbouring tools Traditional Sketching and CAD. Understanding of the manifestation of Digital Sketching in industrial design practice was limited; hence, when and where to further exploit Digital Sketching was rarely explained to designer practitioners. That being so, the conservative and limited use of Digital Sketching in practice can be expected, which could embody untapped design resources.

Existing studies on Digital Sketching in relevant 3D design fields mostly investigated its use with design students (see Chapter 4) rather than with practising designers. However, the designers' insights and their patterns of use of Digital Sketching are critical for understanding the tool and its manifestation in the professional context. This study thus enriches the literature in the industrial design field by providing the results and investigation of Digital Sketching and its neighbouring tools conducted with practising designers.

- As one major contribution to the domain knowledge, the study offers an insight into how designers use Digital Sketching in industrial design practice and why. It systematically shows and explains what designers think about Digital Sketching and their current patterns of use and applications of this tool in practice. Discussions and explorations of where and how Digital Sketching is/can be used during the Early-Middle phases in practice are described with evidence from the investigation. Besides, the study explores the possibilities of Digital Sketching being a transitional tool between Traditional Sketching and CAD. The study findings deepen the domain knowledge by offering a more comprehensive and up-to-date understanding of Digital Sketching from the designers' and industry's perspective.

- Another contribution is that this study has created the Design Tool Characteristics (DTCs) framework for comparing design visualisation tools in the industrial design field (Chapter 2). The framework was originally created in this study for comparing Digital Sketching with its neighbouring tools. However, it could be expanded as an approach to compare other design visualisations tools in relevant 3D design fields due to its comprehensive and universal nature. In the rapidly developing world of design tools, it offers a way to compare and evaluate new,

emerging or hybrid design tools and techniques in the industrial design field. Research projects and results on these design visualisation tools, enabled by the DTCs framework, would further contribute to the domain knowledge.

Along with the DTCs framework, this study also grouped the design visualisation activities into four main tool-use conditions (Chapter 5). Together with our understanding of the industrial design process and the expected deliverables, the DTCs framework and the tool-use conditions are considered a kit for understanding and analysing design visualisation tools in industrial design. The kit contributes to the domain knowledge as a practical and ready-to-use method for conducting design tool analyses in our field.

Additionally, further contributions to the domain knowledge from the study are as follows.

- This study has presented how designers use the design tools in practice, which goes some way towards filling the gap in the literature and thus enriches domain knowledge (Chapter 6).

  In literature, there are studies and textbooks on how to use certain tools theoretically, and why, especially Traditional Sketching and CAD. Many studies on these tools are conducted with students only or with designers in controlled experiments/environment settings. However, how the tools are used in design practice is not studied in detail. This research collected data of tool-use behaviours regarding Traditional Sketching, Digital Sketching and CAD from unobtrusive observations at designers' workplaces. As such, it enriched the domain knowledge by offering industry insights that are lacking in the literature.

- This study identified that the learning experience of a tool in formal education has a long-term influence on one's tool-use behaviours in practice (Chapter 7).

  During the investigation of the use of Digital Sketching in industrial design, the learning experiences of the designers regarding this tool in their formal education seem to play a significant role in their current uses of it. Data in the learning process tool-use condition suggests that some critical issues experienced when learning Digital Sketching may have long-term influences; e.g., User Accessibility and Expertise. This highlights that training in new and emerging tools plays a role in shaping the minds and skill-sets of future designers in their careers.

8.5 Research Reliability and Limitations

The study adopted various techniques during the literature review, experiment design, data collection and analysis to ensure reliability and reduce limitations. First, a broad literature review of design visualisation tools in 3D design fields was conducted to ensure the Design Tool Characteristics (DTCs) framework was comprehensive and universal (Chapters 1 and 2). The research methods in this study adopted both interview and observation approaches (Chapter 4) to understand what designers think about the investigated visualisation tools and, further, to see how they use them in design practice. Limitations of the study are as follows.

There are some limitations to be noted in the study. Specifically, the research activities were primarily conducted in Australia with domestic design firms; hence, the study may have limitations on covering workplace settings in other countries and areas. Due to the time and environment restrictions, the diversity of the participating design firms (Chapters 4 and 6) may not fully represent the diversity of workplaces in industrial design practice in terms of location, culture and size. However, the participants of the interviews and observations in this study are considered diverse in terms of cultural backgrounds, and many of them have international work experience. A more diverse sample set would be useful for further generalising the study results. For example, large international design firms may have compartmentalised the roles of designers more finely than small domestic design consultancies. The types of design firms in this study were chosen because of their potential faster pace in doing various design projects. As the study is aiming to investigate designers' natural use and selection of design visualisation tools, the research was conducted in the manner to ensure minimal impact on this process from the study. Hence, another limitation of the adopted interview and observation approaches is noted that the data collected for the three tools are not evenly distributed as the result of the designers' free selection and use of the three tools.

Since the study chose practising designers as study samples, their availability limited the sample size. Although the data collected from each interview participant are rich, the number of samples might have an impact on reliability. However, the depth of data (in exchange for the breadth of samples) fits the aim of providing an in-depth understanding of how designers see and use Digital Sketching within the time frame of the study. Nevertheless, a larger sample number would still be preferable for increasing the reliability of the results.

In terms of reliability, analysis of interview and observation data was documented, and inter-rater reliability tests were used if required to ensure the reliability of coding. To

control the impact on reliability from the limitations, the Design Research Methodology (DRM) was adopted in this study to intently plan the methods used at different research stages. Various research methods and approaches were used in this study (Chapter 4) to provide an understanding of this emerging design visualisation tool in industrial design and Digital Sketching that reflects its manifestation in practice.

Within limitations, the study explored, experimented, discussed and concluded. A more up-to-date and comprehensive understanding of Digital Sketching and its neighbouring tools is provided, exacted from a less investigated but critical perspective; namely, the industrial design practice.

8.6 Recommendations for Future Research

This study inspires more ideas for future research projects. For Digital Sketching, we can develop and test hybrid techniques with leading-edge technologies for more effective design outcomes. As an instance, when and how to combine Digital Sketching with Cross-reality (XR) technologies for long-distance, real-time immersive design communications in industrial design practice would be worth studying. Another envisioned future project regarding Digital Sketching in industrial design practice would be developing an interactive system or matrix for customising a "roadmap" of when to use Digital Sketching in a design project based on the tool, the designers and the project.

This study established the theoretical barriers and opportunities surrounding Digital Sketching to be a "pathway" to ease the troublesome transition between its neighbouring tools. It would further enrich and deepen our understanding of Digital Sketching in the future by having more field tests with designers and design firms with diverse backgrounds. The cultural diversity of the designers or design firms may provide new perspectives on overcoming the identified barriers. As an instance, the acceptance and share of digital design tools might be higher in some different cultural regions/groups; e.g., Japan or Singapore. Similarly, conducting studies with designers from different sized design firms would also provide new perspectives. Expanding the study to various organisations and disciplines would enrich our knowledge of Digital Sketching.

Exploring the learning experience of design tools in education and its long-term influences on tool-use behaviours and mindsets is another research direction to take. In this study, designers with substantial experience were targeted who had less learning experience of Digital sketching in their education. Hence, some outdated stereotyped thoughts and a limited use of Digital Sketching were identified in their responses/behaviours. A future study with younger designers and new graduates on their perceptions and uses of

Digital Sketching may provide fresh perspectives to view the long-term influences from education.

Moreover, digital design tools are rapidly changing and continuously updating; it could be a challenge for education to keep up-to-date with the industry. Why and how to select, embrace and deliver new design tools and techniques in formal education is challenging but critical for ensuring the success of our future designers. Finally, the DTCs framework, as an approach, can be used to evaluate different design visualisation tools in 3D design fields in future studies, including emerging design tools based on XR technologies and advanced 3D printing, and hence ease this challenging situation. The framework could become the basis for more rigorous quantitative rating of characteristics highlighted for cross-disciplinary uses, which will also be one of the subjects of future study.

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APPENDIX A

Interview Questions

General Information:

How long have you been working as an Industrial/Product designer?
How long have you been in your current design team?
Can you briefly introduce your general design process?
What do you think about Digital Sketching?

1. Which design tools do you use during the early design phase? Why? During the middle design phase? Why? During the late design phase? Why?

2. How long do you usually spend on using Traditional Sketching in a design project? What about Digital Sketching and CAD modelling?
   [Project Example/proportion]

3. Did you learn how to use Traditional Sketching, Digital Sketching, and CAD Modelling in your formal design education? If so, how long did you spend on learning and practising?

4. How is your experience of learning Traditional Sketching, Digital Sketching, and CAD Modelling?

5. Is it easy to make changes to ideas (flexibility) in Traditional Sketching? What about Digital Sketching and CAD Modelling? E.g. add/undo/erase/dispose of former representations and the number of steps to make changes or add details.

6. Of Traditional Sketching, Digital Sketching, and CAD Modelling, which is easier and more effective for moving between design ideas (different solutions)?

7. Of Traditional Sketching, Digital Sketching, and CAD Modelling, which is more helpful for developing details and variations of one/the same design idea?

8. Are the design tools quick enough to catch up with your creative flow during the design process?

   Follow-up Question: Do you think it is more related to the tool itself or your expertise/skills regarding this answer?

9. What tool and representation do you prefer to **visualise** your ideas in the **early** design phase? Why?

10. What tool and representation do you prefer to visualise your ideas in the **middle** design phase? Why?

11. What tool and representation do you prefer to visualise your ideas in the **later** design phase? Why?

12. Which representation form is more **appealing to** you in the early/middle/later design phase? Why?

13. Are traditional sketches enough to represent the engineering and artistic **details** of your mental images during the design process? What about digital sketches and CAD model renderings?

14. Do traditional sketches offer you enough **imagination space** to reinterpret your design ideas (the solutions not the design problem)? What about digital sketches and CAD model renderings?
Reverse: Do the representations display your ideas in a more **constrained/unambiguous** way?

15. Are traditional sketches **accurate enough** to match your mental images during the design process? What about digital sketches and CAD model renderings?

16. Which tool will inspire/help you to **rethink** the design problem, which means reconstructing your understanding of the design problems not the design solutions?

17. **When** do you choose to **change tools**/media during the design process? **And why** do you think you switch to other tools?
Follow-up Question: If you make the choice to decide when to change tools, do you think there will be some differences? (**Organisational versus Individual**)

18. Do you feel you **commit** more to the idea after you change tools? (Depends on tools used by the participant.)

19. During the **switches** of tools in the design process, what do you usually do and how is your experience?

20. During the **switches** of tools, do you think the tool is easy for capturing all the design information from the previous design representations?
Follow-up Question: Do you also use other tools to assist your work when you do traditional sketches? What about when you do digital sketching and CAD Modelling?

21. What kind of representation do you use to communicate your ideas with your teammates or other professional designers/engineers in different design phases? Why?

22. When do you **communicate** your ideas with your clients or other non-designer stakeholders? What kind of representation do you use in different design phases? And why?
Follow-up Question: If the time and/or the representation of external communication is decided by you (not the team leader/ manager), how and when will you do it? Why?

23. How many traditional sketches do you usually use to evaluate or work with your ideas at one time? What about digital sketches and CAD model renderings?

24. Of sketches and the operation interfaces of CAD Modelling & Digital Sketching, which one offers you a better overview of your design?

25. Which tool and its outcomes are more convenient to access and use?

APPENDIX B

Observation Follow-up Questions

Date:

Participant:

Project Role:

Project Design Stage: □ Early □ Middle □ Late

Tools Used: □ Traditional Sketching □ Digital Sketching □ CAD

Representation Audience: □ Self □ Team □ Clients or other non-designer stakeholders

1. Do you feel that you externalised your ideas smoothly and quickly with the tool?

2. Did you change or modify your original ideas during the last 20 mins? How many times roughly?

3. The time you spent to achieve the result with this tool, was it efficient?

4. Did you experience any inconvenience during the use of the tool?

APPENDIX C
Ethics Approval and Completion

SHR Project 2018/110 - Ethics clearance

Astrid Nordmann <anordmann@swin.edu.au>
Wed 23/5/2018 7:45

To: Charles Ranscombe <cranscombe@swin.edu.au>
Cc: RES Ethics <resethics@swin.edu.au>; Sally Fried <sfried@swin.edu.au>; Simon Jackson <simonjackson@swin.edu.au>; Wenwen Zhang <wenwenzhang@swin.edu.au>; David Radcliffe <dradcliffe@swin.edu.au>

To: Dr Charlie Ranscombe, FHAD

Dear Charlie,

SHR Project 2018/110 - Design Tool Characteristics: Mapping the Use of Digital Sketching in Early-Middle Industrial Design Phases
Dr Charlie Ranscombe, Dr Simon Jackson, Wenwen Zhang (Student) – FHAD/Prof David Radcliffe – FSET
Proposed duration: 23-05-2018 to 15-02-2020 [adjusted]

I refer to the ethical review of the above project by a Subcommittee (SHESC2) of Swinburne's Human Research Ethics Committee (SUHREC). Your responses to the review as emailed on 10 May 2018 were put to the Subcommittee delegate for consideration.

I am pleased to advise that, as submitted to date, ethics clearance has been given for the above project to proceed in line with standard on-going ethics clearance conditions outlined below.

- The approved duration is **23 May 2018** to **15 February 2020** unless an extension is subsequently approved.
- All human research activity undertaken under Swinburne auspices must conform to Swinburne and external regulatory standards, including the *National Statement on Ethical Conduct in Human Research* and with respect to secure data use, retention and disposal.
- The named Swinburne Chief Investigator/Supervisor remains responsible for any personnel appointed to or associated with the project being made aware of ethics clearance conditions, including research and consent procedures or instruments approved. Any change in chief investigator/supervisor, and addition or removal of other personnel/students from the project, requires timely notification and SUHREC endorsement.
- The above project has been approved as submitted for ethical review by or on behalf of SUHREC. Amendments to approved procedures or instruments ordinarily require prior ethical appraisal/clearance. SUHREC must be notified immediately or as soon as possible thereafter of (a) any serious or unexpected adverse effects on participants and any redress measures; (b) proposed changes in protocols; and (c) unforeseen events which might affect continued ethical acceptability of the project.
- At a minimum, an annual report on the progress of the project is required as well as at the conclusion (or abandonment) of the project. Information on project monitoring and variations/additions, self-audits and progress reports can be found on the Research Intranet pages.
- A duly authorised external or internal audit of the project may be undertaken at any time.

Please contact the Research Ethics Office if you have any queries about on-going ethics clearance, citing the Swinburne project number. A copy of this email should be retained as part of project record-keeping.

Best wishes for the project.

Yours sincerely,
Astrid Nordmann
(for Sally Fried, SHESC2 Secretary)

SWIN BUR NE
Dr Astrid Nordmann | Research Ethics Coordinator
Swinburne Research| Swinburne University of Technology
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Subject: Acknowledgement of Report for 20200776-4709
Date: Wednesday, 8 July 2020 at 2:14:29 pm Australian Eastern Standard Time
From: donotreply@infonetica.net
To: Charles Ranscombe
CC: RES Ethics

Dear Charles ,

The report submitted for your project 20200776-4709 Design Tool Characteristics: Mapping the Use of Digital Sketching in Early-Middle Industrial Design Phases relating to the end of student involvement has been approved.

Regards,

Dr Ann Gaeth

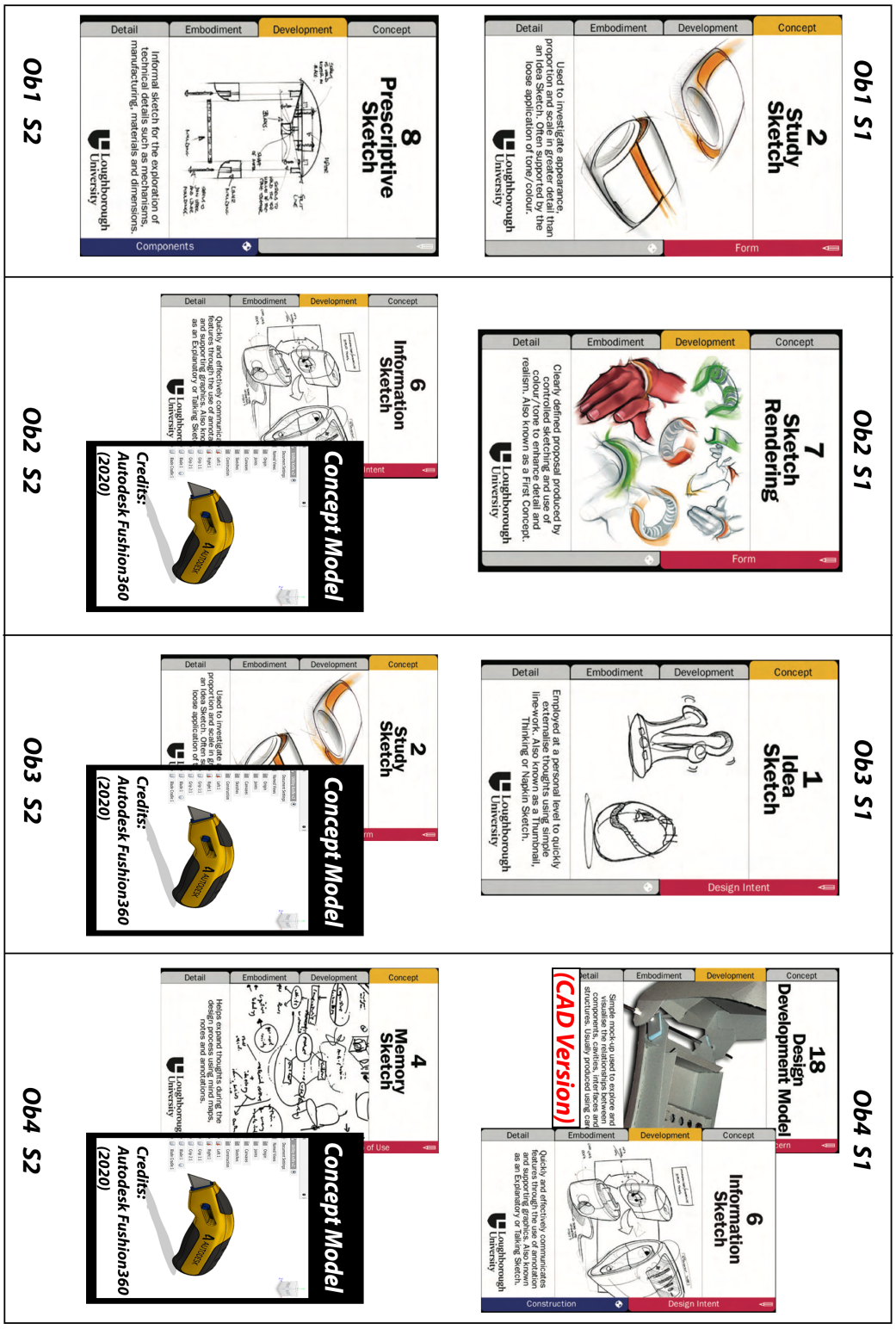
Research Ethics Office

Swinburne University of Technology

P: 92148356 | E: resethics@swin.edu.au

APPENDIX D

Visual References of Resulting Design Representations from the Observations



APPENDIX E

Sample of Interview Data and Coding

Sample: 48 Interview comments
2 citations for each DTCs
Average 3 - 4 citation from each participant

Distribution across the three tools:
Traditional Sketching (TS): 12 citations
Digital Sketching (DS): 16 citations
CAD: 20 citations

Distribution across four tool-use conditions:
Similar to the overall data distribution
Externalisation: 33 References
External Communication: 7 References
Internal Communication: 4 references
Learning Process: 4 References

No.	Design Tool Characteristics	Examples in Interview Comments
1	Ambiguity	DS: External Communication \\ Participant 12: If it's just a rendered Photoshop drawing, it still has that element that as a drawing so people(clients) could kind of feel like either imagining the detail by themselves. CAD: External Communication \\ Participant 9: we all generally agree that it (CAD) is better because there is less of an opportunity for them (Clients) to miss understand what you are doing.
2	Lateral Transformation	TS: Externalization\\ Participant 2: I think the most basic one would be just a pen and paper to start sketching and ideating around the product or what you are designing and trying to get as many ideas as possible down on the paper. CAD: Externalization\\ Participant 8: CAD modelling, I've always been taught to try to avoid ideating in CAD because it can be quite difficult to backtrack and make changes and then you often can end up limiting yourself to a particular form because of that.
3	Vertical Transformation	CAD: Externalization\\ Participant 12: But maybe the CAD would be faster for different type of changes. If we are talking about material change and we are using rendering, so "Can we make this thing red or blue?" then CAD is faster for dropping different material. DS: Externalization\\ Participant 12: With digital sketches, I probably start with one base like have my hand sketched outlines and produce variations based on that, so keeping the form the same but playing around with colours or certain line work.
4	Level of Commitment	CAD: External Communication\\ Participant 7: I don't like to get into CAD too early because in my experienced, if you're presenting a really nice beautiful CAD model to a client and it's quite early on, sometimes they perceive that as more finished product or that's something has been locked in then it's not as free to change. DS: External Communication\\ Participant 8: That's more at the concept development stage where the client hasn't yet seen any of the concepts. It can be preferable to use digital sketching before moving into CAD to avoid the client thinking that they are locked into a particular idea.
5	Level of Aesthetics	DS: External Communication\\ Participant 3: I think at a certain level digital sketches have more "wow" factor to the clients.

		TS: External Communication\\ Participant 4: There is nothing wrong with showing some scratchy hand sketches. I mean obviously there's some hand sketches that you probably eliminate because as an individual and as an organisation, you want to be able to show some level of skill or some level of professionalism.
6	Accuracy	CAD: Externalization\\ Participant 3: Actually, a lot of the time, I will grab a CAD underlay and I will print out certain settings. Even if it's a CAD model that we have created right at the very start (it is literally just cylinders of a certain proportion and a button in a certain place. We will get that as an underlay and we can sketch over that making sure that we've got certain dimensions that are fixed. DS: Externalization\\ Participant 8: I would say the digital sketching was almost a transition between my hand sketching and the CAD so it begins to come more accurate but because you're still not constrained by dimensions like you are in CAD yet.
7	Problem Re-framing	CAD: Externalization\\ Participant 10: I often run into problems once I've actually started CAD-ing it and then you have to come up with solutions for that. CAD: Externalization\\ Participant 7: Probably in the CAD stage, I think start becoming a bit more real and you start noticing problems you just would never notice when in sketching, and because of that stage you are also probably doing prototyping and 3D printing based off your CAD model.
8	Amount of Representations	CAD: Externalization\\ Participant 3: The number of CAD models, it depends on the project. It wouldn't be that many, we wouldn’t do concept CAD models more than 4. TS: Externalization\\ Participant 9: I personally tend to sketch more because I have a tendency of getting stuff that doesn't even look realistic because I feel like all the small little ideas that actually just crap, they help me sometimes do help me come up with better ideas because it will be me combining smaller aspect from each idea into one that I care. So I do have a lot more sketches around.
9	Immediacy	TS: Externalization\\ Participant 11: Especially with hand sketching, it's still your body so it's whatever your hand can do. It's coming from your mind straight away. DS: Externalization\\ Participant 12: It (Digital Sketching)’s pretty good and it does take a while that you have to get used to that disconnect between a screen and your hand, but the outcome of freehand is generally as good as just sketching if not better.
10	Flexibility	TS: Internal Communication\\ Participant 9: With the colleagues, mostly hand sketches. It’s fast I guess, and then if there's something that you want to change in the sketch you can just draw over it to convey the point. CAD: Externalization\\ Participant 2: With Solidworks, you really need to define the set of measurements and the actions you want to take it, you don't have that much freedom in order to create multiple ideas.
11	Mobility	TS: Internal Communication\\ Participant 4: Paper is the most flexible because you don't have to switch on a device and there is no risk of a device breaking or crashing, it's just right there all you need is paper and pens and you're good to go. it's the most flexible and you can pass it around to everyone DS: Internal Communication\\ Participant 12: The thing is that I can sit next to someone and do it, it’s a bit difficult if you come to my desk and start using my tablet to show me an idea.
12	User Accessibility	DS: Externalization\\ Participant 8:

		Perhaps digital might be the least accessible at this point just getting access to a Wacom and pen and sitting down to do it on a different computer. TS: Externalization\\ Participant 4: We may start off just with sketching on paper, so I'll get out my ballpoint pens and they're cheap and you can throw them away and they work well, you can control you line weights on your drawings really easily with ballpoint pens. The most accessible would be pen and paper because you can buy them from the supermarket.
13	Level of Detail	CAD: Externalization\\ Participant 9: CAD would be definitely better because in CAD you can have as many details as you want without making you sketch too complicated. CAD: Externalization\\ Participant 7: It (CAD)'s more real, it enables you to put a lot of detail in without getting flooded, having the ability to hide and show certain parts, do cross-sections and makes it easy to describe a design in a lot of detail where with sketching either hand or digital would take a lot a lot of content to explain the same level of detail.
14	Holistic View of Objects	CAD: Externalization\\ Participant 2: In CAD, you can look at all these different angles, zoom in and zoom out, but if you are sketching, you're stuck with a single direction and just like certain angle CAD: Externalization\\ Participant 10: Probably CAD, because sketches often just a couple of views or something whereas in CAD you can really rotate around and see everything and how all the surfaces are interacting.
15	Compatibility	DS: Externalization\\ Participant 8: If you do need to print it(digital sketch) out again and change it by hand and go back into digital, I feel like there's still a much faster workflow by doing it that way DS: Externalization\\ Participant 11: Well the advantage of digital sketching is we can do that really quick rough CAD model and we can spin it in space and then quickly grab a screenshot of that as an underlay and sketch over the top rather than having to do that and then print it out and then sketch.
16	Fidelity	TS: Externalization\\ Participant 1: It is sometimes hard to also draw what you're thinking, mentally and get those ideas on paper. DS: Externalization\\ Participant 9: It's adequate right now, it's probably like 65%-70% of what I'm seeing in my head. If I base my digital sketches of my hand sketches, it definitely helps to achieve the things with hand sketches that I can't achieve, like material finishes that's the biggest one, because if you draw something really troublesome like a concrete with a lot of textures, I find it really hard to achieve on paper, but with digital sketches I can just throw an overlay on make it look like on a concrete.
17	Learning Cost	CAD: Learning\\ Participant 2: And then CAD I learnt at Uni, I was pretty bad at it so I had to keep practicing a lot to improve myself. DS: Learning\\ Participant 6: Digital sketching, that was a bit tougher. It still is, I'm still learning.
18	Use Cost	TS: Internal Communication\\ Participant 7: I tend to just use hand sketches (to communicate with teammates) because it's very quick. CAD: Externalization\\ Participant 2: I do a lot of CAD just like very quick CAD that I can create everything maybe maximum 5 minutes so I can have an overall shape sorted

19	Tendency to Mix Tools	CAD: Externalization\\ Participant 11: I'm still always sketching to work things out in CAD. CAD: Externalization\\ Participant 9: I still do sketch when I am CAD-ing, but it's really rough ones in certain scenarios when you're CAD-ing then you realise “I didn't take into account of this bit intersecting with this other bit”, so I will draw a really quick sketch on how the intersection could happen or if I didn't take into account
20	Emotional Commitment to Ideas	CAD: Externalization\\ Participant 1: It’s more locked in in my mind I think once it’s in CAD. I suppose there’s certain hours you put into that one model and by the end of a project you’ve probably spent I don’t know how many hundreds of hours on that one model where you don’t want to throw it all away and start something different again.
21	Expectation	DS: External Communication\\ Participant 12: if we move digitally (Sketching), you kind of want to finish things little bit more maybe because you want to show the perfectionism in you. TS: Externalization\\ Participant 11: So, I was getting frustrated at myself that I couldn't get high quality output. I knew that I could because I have previously done quick sketches, but I haven't done it in so long that I wasn't happy with level.
22	Expertise	CAD: Externalization\\ Participant 2: Based on my skills, No and it’s generally tricky to be able to completely match your hand sketches and CAD. TS: Externalization\\ Participant 11: I think I always had to work really hard at sketching to that good level, like some people they just naturally really good at it, and I can do it but I had to work really hard.
23	User Loyalty	TS: Externalization\\ Participant 4: I love sketching by hand. DS: Externalization\\ Participant 1: I used to use Digital Sketching more. I tend to use it less now and I think it's just because I've always had a personal preference towards hand sketching.
24	User Share	DS: Learning Process\\ Participant 3: So, it (Digital Sketching) was really good to learn and I'm glad I did coz now everyone is doing it. DS: Learning Process\\ Participant 6: Digital sketching for example, I knew nothing, I hadn’t done anything at uni.